1976

An economic analysis of field crop production, insecticide use and soil erosion in a subbasin of the Iowa River

Klaus Friedrich Alt
Iowa State University

76-28,231

ALT, Klaus Friedrich, 1946-
AN ECONOMIC ANALYSIS OF FIELD CROP PRODUCTION, INSECTICIDE USE AND SOIL EROSION IN A SUBBASIN OF THE IOWA RIVER.

Iowa State University, Ph.D., 1976
Economics, agricultural

An economic analysis of field crop production, insecticide use and soil erosion in a subbasin of the Iowa River

by

Klaus Friedrich Alt

A Dissertation Submitted to the

Graduate Faculty in Partial Fulfillment of

The Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Department: Economics

Major: Agricultural Economics

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1976

TABLE OF CONTENTS

CHAPTER I. INTRODUCTION

The nature of agricultural crop production requires a more intimate interaction with the environment than do most other economic activities. Crop production has changed the nature of land involved to a greater extent than other production processes on the millions of acres which have been broken by the plow in the course of man's history. Over these years agricultural crop production has evolved slowly. It has progressed from a gathering activity to a shifting slash-and-burn pattern of crop tillage, then to an extensive stationary pattern until the present final state of a very intensive and highly mechanized system of producing food and fiber has emerged.

This intensive technology has enabled American farmers to produce unprecedented amounts of agricultural products for domestic consumption and for exports. However, society has become aware that there are some undesirable side-effects of this intensive agricultural technology. These side-effects include introduction into the environment of by-products and residuals of the agricultural production processes in amounts that often exceed the ability of the environment to assimilate them. These excesses are defined as pollution. The result of this pollution process is the imposition of monetary and nonmonetary costs upon other users of the environment. As a consequence, society has turned its attention to devise methods of managing these externalities. This study is concerned with some of these side-effects and the potential for reducing the effect of intensive agricultural crop production upon the environment.

This study examined the effects of various strategies to control excess erosion and sedimentation from field crop production in a watershed of the Iowa River in East-Central Iowa. In addition, the environmental effects of certain restrictions on insecticide use were measured in terms of an environmental exposure index. These effects were quantified with the aid of a linear programming model.

In this study, certain pollution problems were not examined. These included the problem of animal wastes and pollution originating in agricultural product processing. Attention was also limited strictly to expected residuals of the crop production process. Thus, such pollution problems as accidental spills or incorrect use of insecticides and the soil erosion on lands other than cropland were excluded from consideration.

Environmental Problems Considered

The two pollution problems studied were soil movement from the cultivated land to waterways and the exposure of nontarget species to insecticides. These two problems are best considered together, rather than in isolation. There is a substantial interaction between soil erosion and exposure to insecticides as well as among the strategies to reduce the environmental damage from either or both factors. For example, a reduction in erosion brought about by a change in crop rotation may require an increase in insecticide use to maintain crop yields, as different crop rotations may be expected to have different insect problems.

Sediment

Erosion represents an undesirable side-effect of soil tillage, namely the movement of soil particles from their site of origin by water or wind. The term "gross erosion" refers to the movement of soil for any distance, no matter how short. However, if all soil that moves is deposited within the crop field of origin, there would be no pollution problem, since no off-site damage would be incurred. The delivery of eroding soil to off-site waterways (where it becomes sediment) is termed "sediment delivery."[1]

Sediment is a pollutant which "occupies space in reservoirs, lakes and ponds; restricts stream and drainageways; reduces crop yields in a given year; alters aquatic life in streams; reduces the recreational and consumptive use value of water through turbidity; and increases water treatment costs. Sediment also carries other water pollutants such as plant nutrients, chemicals, radioactive materials, and pathogens" (46, p. 3).

The quantities involved in erosion make it clearly the largest pollution problem in physical terms. The amount of gross erosion has been estimated as four billion tons of soil nationwide each year, of which three billion tons erode on agricultural and forested lands (10). The erosion of four billion tons of soil may be considered equivalent

[1]While this delivery could be referred to as "net erosion," that term is not used.

to the loss of seven inches of soil from four million acres. While not all of this eroding soil will be transported into the waterways, an estimated one billion tons eventually reach the ocean (91).

The erosion problem in Iowa is consistent with the national erosion situation. The Iowa Water Quality Report (43) states that soil erosion in Iowa in 1974 was at the highest level in 25 years, with 4.5 million acres having gross erosion of more than ten tons per acre. Gross erosion of 40 to 50 tons per acre was not uncommon and reached levels as high as 200 tons per acre in some areas.

The pollution problem in the Iowa River attributable to sediment is unusually high for the part of the state in which it is located. "Suspended sediment concentrations found in the Iowa River have ranged from nine to 4,700 mg/1 in recent years. The annual computed sediment load to Coralville [Reservoir][1] was 1.34 million tons in 1966. This value represents over 475 tons of sediment per square mile of drainage area" (43, p. II-79). While this represents less than one ton of sediment delivered per acre, the average amount of gross erosion is about 3.7 tons per acre,[2] assuming an average 20 percent sediment delivery ratio. Of the rivers in Iowa, only those in Western Iowa, particularly those which have been channelized and straightened, have sediment loads in excess of the Iowa River above Coralville Reservoir.

[1] The Coralville Reservoir forms the downstream termination point of the study area for this thesis.

[2] This average figure includes all land in the drainage area including permanent pastures and forests. The average figure for the tilled acres may be expected to be higher.

The sediment load which is deposited in Coralville Reservoir has attracted widespread public attention. The 5,000 acre lake is a valuable recreation source, and continued enjoyment of this resource may be curtailed if sediment continues to accumulate at present rates. This study will identify and quantify the economic effects of attempts to reduce the sediment contribution from agricultural land use.

Insecticides

Insecticides have a pervasive influence upon field crop production. A total of 57 million crop acres were treated with insecticides in the United States in 1971, with a total cost of $241 million (12). Of this total, $34 million was spent on insecticides on corn in the five Corn Belt states. A total of 154 million pounds of insecticides was applied to the nation's cropland in 1971 (3). Of this total, 15.3 million pounds were applied to corn in the five Corn Belt states. Less than one million pounds were applied to the other field crops (including hay).

The introduction of these amounts of toxic materials into the environment may have far-reaching ecological effects. Apart from decimating the insect populations which they are designed to control, the insecticides can enter the biological food chain, leading to potential damage to nontarget species, including man.

It has not yet been possible to design an insecticide which is perfectly safe for species other than the target insect pests and which degrades to nontoxic metabolites as soon as the insecticidal activity is no longer required. Thus, no presently used insecticide is perfectly "safe" to nontarget species. Despite this inherent danger, insecticides have been used widely, since the benefits of their use have been deemed to exceed the potential environmental cost.

For many years preference has been given to insecticides which have long persistences, since their prolonged insecticidal activity eliminates the need for multiple chemical applications. Recently, the most persistent insecticides, such as DDT, have been withdrawn from use because of concern about the long-range ecological effects of chronic exposure to their residues. However, some of their shorter-lived replacements exhibit a higher acute toxicity. Thus, a possible reduction in the residue levels in the environment may have been accompanied by an increased toxicity of these residues. It is thus particularly difficult to evaluate the overall ecological damage attributable to insecticide residue. The environmental exposure index developed here is an attempt to make such an evaluation possible.

Policy Options

When the agricultural field crop production processes cause undesirable environmental effects, these externalities become targets for public policy discussions. The policy options need to be evaluated within the physical context of the externalities. The two types of pollution considered here fall into the category of nonpoint pollution. This type of pollution is generally defined by contradistinction to point sources. "The term 'point source' means any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged" (80; Sec. 502, (14)). The transport of eroding soil and insecticide residues from cropped fields into the water system is not covered by the intent of the definition for a point source and it is therefore described as a nonpoint source. It is also implicit in this definition that it is technically impossible to associate the sources of nonpoint pollution with the levels of pollutants found in the environment.

The farming practices which are most erosive generally are also the lowest cost methods of production.[1] In this model, the activities which assume row crop tillage on the contour have slightly higher production costs than their straight-row counterparts. Similarly, the costs of terracing additional land raises the total production costs on these acreages, since the annualized terrace construction costs are charged to the crops grown on these acreages. As a result, the adoption of these two erosion-reducing practices would increase each farmer's production costs. The decision of each farmer regarding the adoption of these two

---

[1]While the following argument is couched in terms of erosion, it applies equally well to insecticide use. The individual farmer may be concerned about toxicity and persistence of insecticides only to the degree it impacts adversely upon the applicator, crop yield, or on-farm production costs. Society is likely to be more concerned about the level of pollutants in the total environment. Thus, society may desire farmers to employ insecticides which are more amenable environmentally even if their use will increase farmers' production costs.

practices hinges on his estimation of his on-site benefits from erosion reduction as well as any off-site effects which he may consider. The primary on-site benefit is the conservation of his farm's productive topsoil. His estimation of the on-site value of this soil conservation is tempered by the amount of topsoil remaining as well as the length of his personal planning horizon. In the extreme, a farmer who is faced with a particularly shallow topsoil and who is concerned about maintaining this topsoil for future generations may willingly accept the production cost increase to fulfill his ambitions. In general, it appears that the planning horizon of farmers is not of this length, and thus the valuation which these farmers attribute to the on-site effects is correspondingly lower, resulting in their reluctance to adopt erosion-reducing measures.

From society's viewpoint, the situation presents a different problem. Society has a planning horizon much longer than individual farmers, thus society would prefer to have erosion-control measures adopted even if the on-site benefits will not be substantial until the distant future. In addition, society is very much concerned with the off-site benefits of a reduction in erosion and sediment, since the costs caused by sediment damages are borne by society. In consequence, society would prefer farmers to adopt more erosion-reducing measures than farmers are adopting on their own. This divergence of views has given rise to public programs to cause the socially desired level of pollution reduction.

The situation may be exemplified by Figure 1. At each level of sediment withheld, the social marginal benefit exceeds the private (i.e., the farmer's) marginal benefit. Only one marginal cost curve need be shown, since the social marginal cost is identical to the private marginal cost, i.e., all of the costs of withholding sediment are borne by the farmer. The farmer's optimal decision is to equate his costs and benefits, which implies that he will arrange his production processes to withhold OX_o of the maximum amount of sediment (OX_2) which he could cause. From society's viewpoint, he is not withholding enough sediment, as the social marginal benefit of additional withholdings exceeds the marginal cost. Thus, society may attempt to coerce the farmer to withhold more sediment.

Classification of policies

There are several specific policies available to society in its attempts to reduce pollution from agricultural sources. These are classified by Headley (39) into two major categories. The first of these is internalization of the externalities, i.e., to charge the environmental costs to the polluter. An alternative category includes those policies which change the aggregate agricultural production function by subsidizing development and use of pollution-reducing technology.

Internalization The existence of negative externalities implies that the producer is not paying the full social cost of production due to his neglect of the residuals of the production process. For example, the agricultural producer is not charged for the sedi-

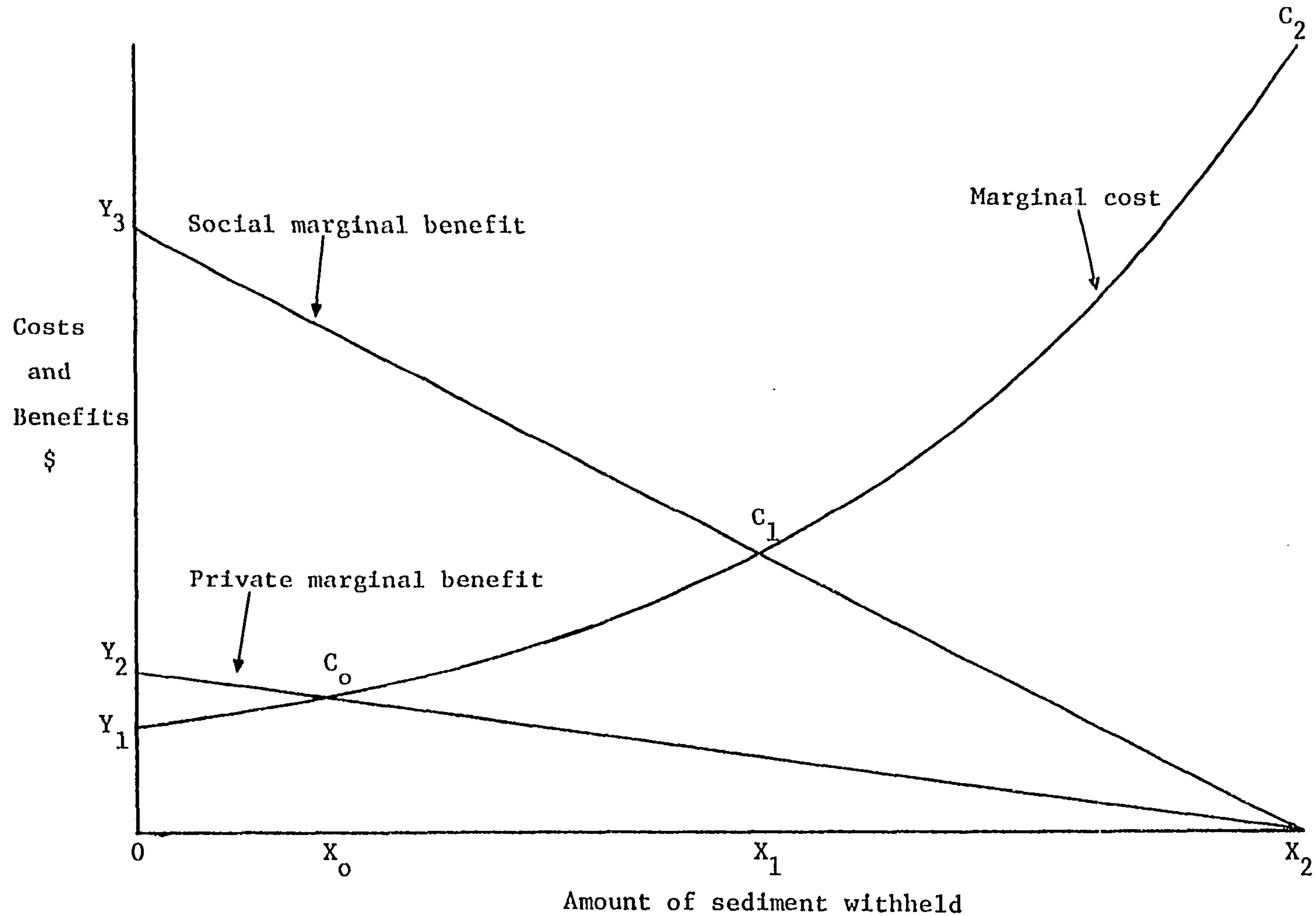

Figure 1. Marginal cost and benefit curves of reducing sediment pollution

ment dredging costs which accrue to society as a result of his sediment-causing tillage activities. The alternative specification was given above, namely that the farmer would not realize all of the social benefits which would accrue if he were to increase the amount of sediment withheld from the environment. Such externalities can be internalized to the producer's decision framework by three distinct methods, namely regulation, charges, and tax incentives or subsidies.

Regulation consists of a socially imposed limit on the polluting production process, either by limiting access to inputs or by restricting residual outputs. Included here are limits on insecticide use by withdrawing registrations of specific insecticides for use on certain crops. Such bans were imposed on DDT, aldrin and dieldrin, and proceedings are in progress to similarly restrict other organochlorine insecticides, specifically chlordane and heptachlor.

A restriction on the residuals is the chosen method in Iowa to decrease the sediment originating from agricultural sources. The state of Iowa has passed a law (22) which requires the landowner to keep erosion from his land below prescribed limits. These limits were established by regional agencies, the Conservancy District Boards, and actual limits may vary among soil classes. The landowner is responsible to undertake reasonable and prudent measures to prevent excessive soil erosion; the choice of which measures to use is his. If he does use erosion control measures approved by the local Conservancy Board, or other reasonable and prudent measures to prevent excessive soil erosion, the landowner cannot be prosecuted under this act for isolated erosion occurrences caused by unusually heavy rainfall or other similar events beyond his control.

The charge approach to pollution control relies upon payment by the polluter for the economic and environmental effects of his actions. This method is based upon the premise that society owns the property rights to the environment and that those who want to use the environment as a receptor of their wastes must reimburse society for the willingness to accept these wastes into the environment.

In agriculture, use of the charge method is practically precluded by the difficulty of identifying beyond doubt the sources of all sediment or insecticide residues and the problem of determining monetary damages for the environmental results of pollution from these sources. Consequently, this method is not used for control of the two pollution problems included in this thesis.

The subsidy approach attempts to cause farmers to withhold more pollution by subsidizing use of certain production processes. An example of such a subsidy is the cost-sharing program available to farmers who construct terraces on their land. Through the cost-sharing program, society reimburses the farmer for a large portion of his construction expenses. The objective is that such subsidies will increase terrace construction and thereby lead to a reduction of sediment in rivers and reservoirs.

Change production function The second pollution abatement category proposed by Headley is the development of new technology which is designed to produce the same level of desired output, but at a reduced level of environmental pollution. The production processes for field crop production now use substantial applications of insecticides. If new production methods can be found which reduce the use of these chemicals (such as integrated pest management), and if farmers can be convinced that their profits will be increased by the new processes, then these new production methods may find wide acceptance. As a result, the use of the environmentally damaging production process will decline. A similar conclusion holds in the erosion case. If nonerosive land tillage methods can be developed which result in crop yields equal to those found in present systems, then these new methods will be used, leading to a reduction in erosion.

This pollution abatement scheme may compliment the regulation method. In those cases where the restriction of an input precludes further use of traditional production methods, alternative production processes have to be developed and adopted. For example, a reduction in gross erosion can be brought about by changing tillage methods (i.e., employing minimum tillage), rotations (i.e., a more extensive rotation), or soil conservation methods (i.e., contour cropping or terracing). Each of these changes represents a change of the production function, not a movement along a constant function. Similarly, the use of insecticides can be reduced by changing crop rotations. As an example, continuous corn was assumed in the model to require treatment against corn rootworm, whereas corn in a corn-soybean rotation was assumed to require no such treatment.

Objectives and Procedures

This study had two major objectives. The first was to improve the application of existing and new analytical techniques to the study of the impacts of environmental policies upon agriculture. The second objective was to identify and quantify the effects of various policies designed to increase the amount of pollution abatement in two cases (erosion and insecticide residues) where negative externalities exist to society resulting from the individual decisions of farmers. The effects to be considered include changes in production costs and methods, farming practices, and land use, as well as environmental quality.

The study estimated the situation which would obtain in the absence of environmental controls. This estimate will be referred to as the "baseline solution" throughout the discussion. Several environmental policies were simulated in this study. The first of these was an absolute limit on gross erosion per acre cropped. This limit was specified at three levels ranging from 10 to 3 tons/acre/year. This specification follows the Iowa Soil Conservancy Law (22), as the maximum permissible erosion under this law will be specified on a per acre basis. The results of the analysis will then indicate directly the effect of the Soil Conservancy Law as imposed upon the study area. Another policy treated the study area as a single planning unit upon which a maximum limit on sediment delivered to Coralville Reservoir could be imposed. Such a limit on the amount of sediment delivered simulates the effect of a water quality standard imposed upon the study area, since water quality and sediment delivery are directly related.

These types of quality standards are potential instruments for area-wide pollution control agencies, and their effects were studied for that reason. A third policy assumed payment of subsidies for construction of terraces and for row crop tillage conforming to the soil slope contours. Subsidies have been paid to farmers to help defray the cost of certain erosion-reducing measures, including terracing. The Iowa Soil Conservancy Law implies that these subsidies will continue, as it states that no landowner can be required to establish particular soil conservation practices unless cost-sharing funds of at least 75 percent of the establishment costs have been made available.

The environmental policies on insecticide use took two forms. One was a "ban" on use of specific insecticides, which allowed for the estimation of the impact of cancelling the registration of certain insecticides. The other policy relied upon an index of the potential environmental damage of insecticide residues. Maximum amounts of this index were imposed upon the study area as limits to crop production.

The physical assessment of the erosion and sediment effects was based upon the Universal Soil Loss Equation (USLE) and sediment delivery ratios. These tools allowed estimation of the gross erosion on cropland and sediment delivered to Coralville Reservoir in each alternative. Chapter II will explain this estimation in detail. The assessment of insecticide residues used an Environmental Exposure Index (EEI). This newly developed index estimated the damage expected from an insecticide load on the environment. The index will be derived and explained in Chapter III.

The economic assessment used a linear programming model to estimate the changes of production methods, location, and costs resulting from the various programs which society could institute. The linear programming model and the derivation of its coefficients will be explained in Chapter IV.

Chapter V will describe each of the alternative policies in detail. The model results will be presented and analyzed separately for each alternative policy. Particular attention will be given to the cost changes caused by these policies. The estimation of the cost changes allowed the computation of a marginal cost function for changes of the levels of both environmental variables. These marginal cost functions will be presented in the last chapter.

CHAPTER II. SOILS IN THE STUDY AREA AND EROSION

No study of this kind can be useful without reference to a specific area with its set of environmental and agricultural constraints and peculiarities. The study area chosen here is located in East-Central Iowa along the Iowa River and includes all of the watersheds of the Iowa River between the Marshalltown River gage and the dam on Coralville Reservoir. The land area totals 938,050 acres or about 1,466 square miles. This study area covers slightly less than half of the total area of 3,115 square miles which drains into Coralville Reservoir.

A large percentage of the land area is tilled for agricultural crops (Table 1). The predominant crops are corn and soybeans. Lesser acreages are planted to oats, which are required, in part, as a cover crop for the hay seedings. The cropland not planted to either the row crops or oats produces hay, primarily alfalfa. The land not suitable for tillage supports permanent pasture and a small amount of forests; the latter occurs typically on rough land, such as next to riverbanks and gullies.

The soil classification system used in this study is based on a land capability classification. This system stratifies all soils into eight soil classes. These classes are differentiated by suitability for agricultural uses, i.e., limitations which may reduce the choice of crops or require conservation practices or both. These eight land classes are further subdivided with four subclasses within each class. These four subclasses give the dominant limitation for agricultural

Table 1. Major land uses of study area in 1967

Crop	Acres[a]	Percent of Area
Corn	310,293	33.08
Soybeans	98,166	10.46
Oats	76,805	8.19
Hay (cropland)	90,109	9.61
Cropland pastured	131,338	14.00
Other cropland	54,878	5.85
Permanent pasture	92,411	9.85
Forests	58,091	6.19
Other	25,959	2.77
Total	938,050	100.00

[a]Source: (70).

use, i.e., whether the soil is subject to particular risks of erosion, climate,[1] wetness and drainage problems, or root-zone limitations (shallow soils). A further level of detail is provided by land capability units which reflect the crop yield and management characteristics of the soil. Thus, at this lowest level of disaggregation, we can identify a parcel of land by its suitability to major agricultural uses, by its limitations imposed by the soil physical characteristics, and by its expected crop yield level. However, this level of disaggregation is so complete that it results in an unmanageable number of subdivisions for purposes of this study. As a result, the land capability units were aggregated into Soil Resource Groups (SRG) on the basis of comparable yield and farming management characteristics. A list of these SRGs, their major component land capability units, and a short description of each is given in Appendix A. Several of these SRGs are relatively small in size and were combined into homogeneous SRG aggregates, as shown in Table 2 in order to reduce the size of the model.

The linear programming model was specified for a land base derived from these SRG aggregate acreages (Table 2). One of the SRG aggregates (D) included all of SRGs 28 and 29. As Appendix A shows, these soils are unsuitable for tillage, since they include smaller areas of stony riverwash and larger areas of steep hillsides with slopes in excess of 14 percent. Since, historically, SRG aggregate D was used only for pasture or remained idle, it was assumed that this SRG aggregate would

[1]This subclass is not found in Iowa, rather only in the arid areas of the Western United States. It is listed here for completeness.

Table 2. Land base of the model

SRG		Cropland Acreage[b]		
Aggregate	Component[a]	Not terraced	Terraced	Total
A	3	274,530	4,240	278,770
B	1	13,114	0	13,114
	2	207,356	3,324	210,680
	Total	220,470	3,324	223,794
C	18	114,831	0	114,831
D	28	0	0	0
	29	0	0	0
	Total	0	0	0
E	10	1,217	0	1,217
	20	27,418	0	27,418
	22	204	0	204
	23	3,097	0	3,097
	Total	31,936	0	31,936
F	4	31,824	637	32,461
G	6	4,949	0	4,949
	12	2,981	0	2,981
	Total	7,930	0	7,930
H	15	5,767	0	5,767
I	13	1,172	0	1,172
K	14	597	0	597
	16	1,116	0	1,116
	Total	1,813	0	1,813
Grand Total		690,273	8,201	698,474

[a]For definitions see Appendix A.

[b]Source: (70).

not support tillage activities and it was thus excluded from the tillage alternatives considered in the model. The land base for all other SRG aggregates was assumed equal to the total cropland acres derived from the aggregation, separated into terraced and unterraced categories. The presently terraced acreages were relatively small (Table 2), and they were concentrated on three SRGs (A, B, and F).

Erosion

Erosion is a natural process which has helped to shape the face of the earth since its beginning. Erosion has reduced the most rugged mountains to smooth hills, and it has cut channels for surface water runoff to flow to the oceans, often creating most picturesque sights in the process, such as in the Grand Canyon. In fact, the beginnings of civilization have been aided by the yearly floodings and deposition of stream-borne sediment on the floodplains of rivers, such as the Nile, Euphrates, and Yellow River. These floods fertilized the soils and allowed the establishment of sedentary agriculture, requiring the development of social systems capable of dealing with the resulting population concentrations. In modern-day agriculture, these floods are no longer found desirable. In consequence, the negative effects of erosion are considered paramount. Several such negative effects are identified, both on-site and off-site. The on-site effects include the eventual elimination of the most productive topsoil, which will lead to a lowering of the expected crop yields. Other on-site effects relate to changes in farmability due to the creation of gullies or other erosion-induced land changes.

The off-site effects include all effects of sediment in the waterways of the environment. As the concentration of sediment in the water increases, certain changes in the water environment may occur. The biological activity in water depends upon the presence of sunlight, which could be excluded if the water is clouded with suspended sediment. Consequently, the ability of the water system to produce fish or shellfish for commercial or recreational harvest may be impaired by high concentrations of suspended sediment.

Sediment also has undesirable downstream effects. The sediment load in a waterflow can be deposited at any point where the speed of flow is reduced. A prime example of this effect is the progressive siltation of lakes and reservoirs, leading to an eventual complete filling of lakes and reservoirs with silt. The resulting costs to society include the loss of use of the body of water, whether for recreational use, for water storage as flood protection, or for other uses. In those instances where a shipping lane is closed by sediment deposition, dredging costs are also incurred. Other indirect costs are caused by an increase in the amount of total flow due to the suspended sediment, such as more frequent flooding, larger stream channels and the like.

While it may seem desirable to eliminate the amount of sediment carried in water, such a possibility is precluded by the forces of nature. Erosion occurs on all parcels of land, not only those used in agricultural production. In fact, the erosion on construction sites, mining areas, or the like can be an important contributor to the sediment loads in specific areas. Sediment is also produced by stream bank erosion and caving-in of bank overhang. This bank erosion is a significant factor in sedimentation of Coralville Reservoir, as the Iowa River above Coralville meanders widely. However, the present study will examine only the contribution of agricultural land use to sediment production.

The estimation of the amount of sediment generated by various agricultural production methods involves three distinct questions: First, what amount of soil is moved within the field, i.e., the gross erosion; second, what percentage of the gross erosion is actually deposited into the waterways, i.e., the sediment delivery ratio; and third, what percentage of the sediment entering the water is moved downstream, i.e., the sediment transport ratio. Of these three, the sediment transport ratio is assumed in this study to equal 100, which implies that all sediment which enters a creek in the watershed will eventually be transported to Coralville Reservoir. This assumption appears realistic in view of the relatively short distances the sediment has to travel to reach the reservoir. Further, inspection of the creek and rivers in the study area shows that sediment deposition is only transitory until the reservoir is reached.[1] The estimation of gross erosion and sediment delivery is detailed in the following discussion.

Gross erosion

The generally accepted estimation method for gross erosion uses the Universal Soil Loss Equation (USLE). This equation was developed by Wischmeyer and Smith from numerous research results spanning a time period of many years (96). The function was designed specifically to relate the effects of various crop growing practices to the resulting gross erosion.

The USLE predicts the amount of soil which is moved within the field by the force of rainfall striking the soil and by the surface water runoff. Much of this soil is redeposited in grassed areas or on flatter ground and does not actually leave the field. The soil loss equation has the form:

$$E = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

where: E is the gross erosion in tons/acre/year.

R is a factor to account for the amount and distribution of rainfall in the local area, i.e., whether rain occurs in gentle mists or in devastating "gully washers."

K is an erodibility factor unique to the particular soil, determined by the physical characteristics of the soil, such as sand and silt content.

[1]The reservoir itself has a high sediment trapping efficiency. Well over 90 percent of the suspended sediment entering the reservoir is deposited there (14).

L is the slope-length factor; other things being equal, on a longer slope the erosion will be higher due to the higher head of the runoff.

S is the slope-gradient factor; the steeper the slope, the greater will be the velocity of the runoff water, and thus more soil will be eroded.

C is the crop management factor; this factor is unique to each crop or crop rotation in each area. It relates the amount of crop cover or residue on the soil surface at specific intervals in the growing season to the amount and severity of rainfall occurring during such periods. More crop cover will cause lower gross erosion.

P is the erosion control practice factor, such as terracing or contouring. These practices slow runoff water, thus reducing its erosive capability.

The coefficients for several of these factors specific to the study area are given in Table 3. The SRGs with slopes of one percent were assumed to have no measurable soil loss. A slope of one percent designates essentially flat land, and the length of the "slope" is practically undefined. The C factor was computed for each rotation and tillage practice from SCS data specific to Iowa (86). Using the provided factor values, an estimate of the gross erosion specific to each crop production activity of the model was computed with the Universal Soil Loss Equation. The computations were made separately for each soil component of each SRG aggregate; only the resulting soil loss estimates were averaged to arrive at a weighted average for each production activity by SRG aggregate. This method is preferable to averaging the USLE coefficients for the soils in each soil aggregate and computing the soil loss from average coefficients, since such a method

Table 3. Soil loss equation coefficients by Soil Resource Groups[a]

SRG	Rainfall R	Erodibility K	Slope Length L	Slope Gradient S	Practice Factor P
			(feet)	(percent)	
2	180	.32	369	3	.5
3	180	.37	308	9	.6
4	180	.37	257	16	.8
6	180	.43	238	9	.6
10	180	.43	221	2	.6
12	180	.43	221	11	.6
13	180	.17	338	7	.5
14	180	.24	374	2	.6
15	180	.24	346	9	.6
16	180	.24	327	3	.5
28	180	.37	235	19	.9
29	180	.32	390	16	.8

[a]Contouring was assumed not to occur on land with less than 2 percent slopes. Thus SRGs with slopes of less than 2 percent are not listed in this table. Source: (84).

would lead to an erroneous estimation of soil loss.

Sediment delivery ratio

The USLE computations yield the gross erosion from sheet and rill erosion specific to each crop production activity. These erosion estimates are summed for the activity levels of the production activities which enter each model solution to estimate the gross erosion for each SRG aggregate and for the whole study area. This total amount does not equal the amount of sediment delivered to Coralville Reservoir. "To compute the sediment yield in the drainage area, this estimate [of total erosion] must be reduced to compensate for deposition at the toe of field slopes, in field boundaries, in depressions, in constructed sediment basins and traps, and along the path traveled by the runoff as it moves from the field to a stream. Sediment additions from sources along this path must also be taken into account" (95; p. 7). There are no useable deposition equations or estimation methods for sediment additions from gully, streambank, and channel erosion. A sediment delivery ratio is typically used as an estimate for all changes of the sediment amount between the field and the waterway. The resulting estimate of sediment delivered into water is a "long time average for the particular watershed conditions" (95; p. 7).

The estimation of these sediment delivery ratios has to account for the specific topography. Since even the relatively small study area presents wide variations of topography, it would not suffice to apply a single ratio to the whole watershed. Therefore, a sediment delivery ratio was estimated for each of the 18 watersheds of the study area (Table 4). The sediment delivery ratios used in the model for each SRG aggregate were computed as the average of the watershed delivery ratios weighted by the occurrence of each SRG aggregate within each watershed. The delivery ratio represents the percentage of the gross erosion (as estimated by the USLE) which is delivered into the river system.

Table 4. Watersheds in the study area

Code	Stream Name	Drainage area[a] Sq. miles	Acres	Sediment delivery ratio[b]
12	Burnett Creek	32.4	20,740	18.0
13	Linn Creek	66.8	42,750	11.0
14	Timber Creek	124.0	79,360	10.0
15	Deer Creek	85.6	54,790	10.0
16	Sugar Creek	21.6	13,820	21.0
17[c]	Direct Tributaries, Marshalltown to Deer Creek	89.6	57,340	6.0
18	Richland Creek	60.3	38,590	16.0
19	Otter Creek	41.2	26,370	8.3
20	Salt Creek	223.0	142,720	4.0
21	Walnut Creek	91.3	58,430	12.0
22	Honey Creek	29.9	19,140	21.0
23	Bear Creek	222.0	142,080	7.0
24	Direct Tributaries, Deer Creek to Marengo above Bear Creek	142.3	91,070	3.6
25	Hilton Creek	21.5	13,760	22.0
26	Price Creek	30.9	19,780	12.0
27	Knapp Creek	30.6	19,580	15.0
28	Hoosier Creek	48.8	31,230	13.0
32[c]	Direct Tributaries, Marengo thru Coralville Reservoir	189.2	121,090	5.0

[a]Source: (84).

[b]Source: (14).

[c]Only part of this watershed is included in the study area.

CHAPTER III. INSECTICIDES AND THE ENVIRONMENTAL EXPOSURE INDEX

The organic insecticides used in field crop production in the study area are classified in three general groups. These three groups are the organochlorines, the organophosphates and the carbamates. Those insecticides of each group which are included in this study are listed in Table 5. There are also inorganic insecticides, such as the arsenicals, which cannot be included in this classification, but these chemicals are not presently used in significant amounts.

The organochlorine (or chlorinated hydrocarbon) insecticides have been used widely over the last 30 years. As a group, these chemicals are characterized by long persistence, low cost, and good insecticidal usefulness. Their method of insecticidal action appears to be through interference with nerve transmissions (66). This, together with their known lipid solubility, would explain the selective toxicity of these chemicals to arthropods. Arthropods have little or no myelin, that is, fatty cover of their nerves, and the chemical can attack the nerves without interference. In contrast, the nerves of vertebrates are heavily myelinated, and the chemical is trapped in this fat before reaching the nerve.

The organophosphate insecticides constitute the largest and possibly most diverse group of insecticides presently in use. Some of the organophosphates, such as parathion, are very toxic, while others exemplified by malathion are of low toxicity to mammals. In fact, some compounds are sufficiently nontoxic to mammals that they can be used

Table 5. Insecticides

Insecticide group	Name: Common	Name: Chemical
Organochlorine	Chlordane	1,2,4,5,6,7,8,8-Octachloro-2,3,3a,4,7,7a-hexahydro-4,7-methanoindane
	Heptachlor	1,4,5,6,7,8,8-Heptachloro-3a,4,7a-tetrahydro-4,7-methanoindene
	Toxaphene	Chlorinated camphene
Organophosphate	Diazinon	O,O-Diethyl O-(2-isopropyl-4-methyl-6-pyrimidinyl) phosphorothioate
	EPN	O-ethyl O-p-nitrophenyl O-phenyl phosphonothioate
	Ethoprop	O-ethyl S,S-dipropyl phosphorodithioate
	Fensulfothion	Phosphorothioic acid, O,O-diethyl O-[p-(methylsulfonyl) phenyl] ester
	Fonofos	O-ethyl S-phenyl ethylphosphonodithioate
	Phorate	O,O-Diethyl S-[(ethylthio) methyl] phosphorodithioate
	Terbufos	O,O diethyl S-[(tert-butylthio)-methyl] phosphorodithioate
	Trichlorfon	Phosphonic acid, (2,2,2-trichloro-1-hydroxyethyl) dimethyl ester
Carbamates	Carbaryl	N-Methyl-1-naphtyl carbamate
	Carbofuran	2,3-dihydro-2,2-dimethyl-7-benzofuranyl methyl carbamate

as systemics against livestock ecto- and endoparasites. The primary mode of activity of the organophosphate insecticides is to irreversibly inhibit insect cholinesterase (65).

The third major group of chemicals, the carbamates, has been developed in response to increased resistance of insect populations to certain insecticides of the other two groups. In most respects (except for chemical structure), the carbamate insecticides are quite similar to the organophosphates. The insecticidal action appears to be analogous to that of the organophosphates, namely through inhibiting the cholinesterase. However, the precise mechanism seems to be slightly different, and other poisoning mechanisms also appear to be responsible for the toxicity of certain carbamates (65).

Decomposition of Insecticides in the Environment

Factors affecting decomposition

Like all other organic materials, the organic insecticides will eventually decompose into carbon dioxide, water, and other final oxidation products. The speed of this degradation is by no means uniform among chemicals. Even a specific insecticide can exhibit a significantly different persistence under varying environmental regimen, since many environmental factors influence persistence. There are seven factors known to influence the fate of pesticides in soils: decomposition by either chemical, photochemical, or microbial means; volatilization; physical movement; plant or organism uptake; and adsorption (8). These factors have been grouped into four classes, listed below in decreasing order of significance (26).

Primary factors Included here are all factors related directly to the chemical structure of the insecticide, such as intrinsic stability, solubility and volatility. A chemical which is chemically stable, highly insoluble in water, and slightly volatile will certainly persist longer in the environment than a chemical lacking these characteristics. It also follows that management of the soil can speed pesticide disappearance, as frequent disking of the soil has been suggested as a method for reducing the residue levels of volatile insecticides in soil (58). It should be noted that the present work is concerned only with the pesticide residues in soil, including those residues adsorbed to eroding soil. The question of the environmental damage attributable to volatilized insecticides will not be addressed here, due to the rather complete lack of data on this subject. It has, however, been suggested that this may be a minor environmental factor due to the tremendous dilution of the toxic material in the atmosphere. "It appears that the atmosphere of certain rural villages, in the United States, surrounded by substantial cultivated acreages, may contain about 20 $\mu g/m^3$ (about 16 ppb) of organo-chlorine compounds during the application period. But that appears to be a special case, since, on the average, the concentration in the atmosphere is substantially lower, centering about $1 \mu g/1000 m^3$ (about 0.8 ppt)" (40). The same source computed that the average value represents 1/40000 of the "daily acceptable dose" set by the World Health Organization.[1] It has also been suggested that the oxygen in the air combined

[1]The "daily acceptable dose" is defined by the World Health Organization as the dose whose ingestion over a lifetime does not present appreciable health risks (40).

with the catalytic action of sunlight will oxidize most organic compounds very rapidly. Thus, organic chemicals which are volatilized and are intimately mixed with this oxydizing agent may be destroyed quickly (27).

Secondary factors These factors are related to the soil environment to which the insecticide is applied, primarily by influencing speed and extent of adsorption. Adsorption is related to the organic matter and clay contents of the soil and may be influenced by the soil structure. Rainfall should also be listed here, since it will determine the extent of leaching (if any) and desorption.

Tertiary factors The temperature of the soil environment may have significance, since most disappearance is slowed down, if not stopped altogether, at lower temperatures. The cultivation of the soil (and in association, the crop rotation) may also be a tertiary factor, since the disappearance of certain insecticides seems to be related to incorporation of the chemical into the soil. The natural microbial population of soil may be listed here also, but it is probably not a limiting factor as it can usually multiply quite rapidly when and if needed.

Quaternary factors The final group includes all other factors, such as soil pH, soil mineral content, amount of surface plant cover and the like. These factors may be of significance for certain insecticides, but, in general, their influence is slight.

Decomposition time path

This decay of insecticides is of particular ecological significance, since it implies that residues of organic insecticides will reach a certain maximum level, as determined by the periodic application rate and the chemical persistence, rather than to increase without limit over time. This point can be illustrated by an example. We assume that one pound of a particular insecticide per acre is applied each year, say at planting, and that this insecticide decomposes at the rate of 50 percent each year, i.e., that the chemical half-life is one year. At planting in the second year, one-half pound of insecticide remains from the first-year's application. The addition of the second yearly application makes the total chemical amount in the environment equal to 1.5 pounds per acre. At the time of the third yearly application, this residue will have decomposed by 50 percent. Therefore, the third annual application will raise the chemical content to 1.75 pounds per acre. This amount, in turn, will decompose by 50 percent within one year, so that after the fourth application has been made one year later, the total chemical level will be 1.875 pounds per acre. If these applications continue at the same level over a number of years, eventually a maximum level of two pounds per acre will be reached. This maximum level will occur once each year, namely immediately following the yearly application.

The insecticide residues will decrease during the year between applications in a manner described by a certain decomposition formula. The timepath of this decay can be described by a first-order kinetic degradation function, which is the simplest kinetics likely to be encountered under practical conditions (36). The distinguishing characteristic of a first-order kinetic degradation is that the relationship between time and the logarithm of chemical concentration is linear, i.e., that a constant percentage of the starting concentration decays in a given time period. This implies also that the chemical has a constant half-life at all concentrations.

Mathematically, a first-order kinetic degradation function can be described by the following form:

$$f_t = e^{-rt}$$

where f_t = residue remaining at time t, expressed as a fraction of the initial amount;

r = a constant which specifies the speed of degradation;

t = time elapsed since application.

From the formula provided by Hamaker (36), it follows that the specific form of the function applicable to the first order kinetic degradation of insecticides is:

$$f_t = e^{\frac{-\ln(2)t}{h}}$$

where f_t = residue remaining at time t, expressed as fraction of initial amount;

h = half-life of the insecticide, in years;

t = time t elapsed since application, in years.

Specifically, the fraction f_1 remaining at one year following the application is:

$$f_1 = e^{\frac{-\ln(2)}{h}}$$

Similarly, the fractions f_2 and f_3 remaining at two and three years following the application are:

$$f_2 = e^{\left(\frac{-\ln(2)}{h} \cdot 2\right)} = f_1^{\ 2}$$

$$f_3 = e^{\left(\frac{-\ln(2)}{h} \cdot 3\right)} = f_1^{\ 3}$$

If equal amounts of the insecticide were applied over n number of years, the amount of chemical residue in the environment immediately after the nth application would be described by:

$$r = A(1 + f_1 + f_1^{\ 2} + f_1^{\ 3} + \ldots + f_1^{\ n-1})$$

where r = maximum residue level;

A = yearly application rate.

In the limit as $n \rightarrow \infty$, this series simplifies to:

$$r = A\left(\frac{1}{1-f_1}\right)$$

This last equation then describes the maximum residue (r) which will occur once a year, namely immediately after application. The decay from this maximum level in the time period between applications will of course follow the same degradation function as was described above.

Consequently, if one application is made each year, the residue amount r of an insecticide at time t since the last application can be expressed by:

$$r_t = A \cdot \frac{1}{1-e^{\left(\frac{-\ln(2)}{h}\right)}} e^{\left(\frac{-\ln(2)t}{h}\right)}$$

In the general case where the application frequency may differ from once each year, the above equation has to be augmented:

$$r_t = A \cdot \frac{1}{1-e^{\left(\frac{-\ln(2).m}{h}\right)}} e^{\left(\frac{-\ln(2)t}{h}\right)}$$

where m = time interval in years between applications of the insecticide.

Indices of Environmental Effects of Insecticide Use

Insecticides have two side-effects which cause environmental concern about their use. Specifically, these side-effects include their persistence in the environment and their toxicity to nontarget species. An ideal insecticide would persist only until all target organisms are controlled and would be nontoxic to all other organisms. Unfortunately, no such ideal chemical exists. In fact, all insecticides exhibit either (or both) of the side-effect problems to varying degrees. It is, therefore, possible that an attempt to minimize the problem of persistence by a shift in use of insecticides may actually cause an increased problem of toxicity. The implied trade-off of persistence versus toxicity can be evaluated only if a "common denominator" can be found specifically for that purpose. Such a common denominator can be found in an environmental index. Two such indices have been developed previously; they are discussed below. Based upon this earlier work, an improvement in the index specification will be presented later in this chapter.

Potential environmental hazard

Weber (92) proposes an index which he calls "Potential Environmental Hazard" (PEH) based upon four factors: (1) mobility, (2) longevity, (3) toxicity, and (4) biomagnification. The definitions of these factors are given in Table 6. Each pesticide is assigned a rating for each of these factors, and the ratings are then combined (by multiplication) to give the pesticide's PEH value.

Three of the factors require further definition. Longevity seems to be defined by Weber as the chemical half-life; this is not spelled out clearly in his discussion. Toxicity is defined by Weber as the toxicity of the pesticide to fish, either to rainbow trout or bluegill or both. The toxicity is expressed as the lethal concentration for 50 percent of the test species in a given time period which varies from 24 to 96 hours. The biomagnification variable is defined on the basis of experimental data. Organisms such as oysters or fish were placed into specified concentrations of each chemical. After a time period of 24 to 96 hours, the organism is analyzed for its absorption of the chemical. This analysis is reported in a ratio (R) of the chemical concentration in the organism compared to chemical concentration in the surrounding water.

Table 6. Definition of factors of potential environmental hazard index[a]

Factor	Value	Rating	Definition
Mobility	1	immobile	cationic; water solubility < 5 ppm; presence of Mn, Zn, Hg, Cu, Sn, Ca, K, or NH_4
	2	intermediate	basic; 5 ppm < water solubility ≤ 500 ppm; presence of P or As
	3	mobile	acidic or amionic; water solubility > 500 ppm
Longevity[b]	1	readily degradeable	chemical lasts less than 1 month
	2	moderately degradeable	chemical lasts from 1 to 6 months
	3	slowly degradable	chemical lasts from 6 to 18 months
	4	persistent	chemical lasts longer than 18 months
Toxicity[b]	1	nonhazardous	LC_{50} > 100 ppm
	2	slightly hazardous	1 ppm < LC_{50} ≤ 100 ppm
	3	hazardous	0.01 ppm < LC_{50} ≤ 1 ppm
	4	toxic	LC_{50} ≤ 0.01 ppm
Biomagnification[b]	1	nonaccumulative	$R \leq 1$
	2	slightly accumulative	$1 < R \leq 10$
	3	moderately accumulative	$10 < R \leq 1000$
	4	highly accumulative	$R > 1000$

[a]Adapted from (92).

[b]These variables are described in the text.

Weber provides numerical data for 52 pesticides. Of these, six insecticides are included in this study. The data for these six insecticides are given in Table 7. The computation of the PEH value is multiplicative. Thus, the maximum PEH value and the greatest potential hazard would be 3 x 4 x 4 x 4 = 192.

Environmental harm coefficient

An "environmental harm coefficient" based upon the insecticide toxicity and the rate of decomposition was presented by Dixon, Dixon, and Miranowski (24). These environmental harm coefficients were multiplied by the insecticide use to yield estimates similar to the index presented here. The functional form used in this earlier work could be simplified as:

$$I = \sum_j \frac{A_j}{d_j \cdot LD_j}$$

where I = value of the index;

j = 1 to n insecticides;

A_j = amount of use of insecticide j, in pounds;

d_j = decomposition rate of the chemical in the environment;

LD_j = lethal dose of insecticide j to 50 percent of test animals (the standard toxicity measure).

Both of the indices lack some precision since both will not differentiate insecticides of the same chemical group sufficiently to allow policy decisions on the use of specific insecticides. Thus, while

Table 7. Potential environmental hazard values for selected insecticides[a]

Chemical	Factors				PEH value
	Mobility	Longevity	Toxicity	Biomagnification	
Organochlorines					
Chlordane	1	4	4	4	64
Heptachlor	1	4	4	4	64
Toxaphene	1	4	4	4	64
Organophosphate					
Phorate	2	1	4	1	8
Carbamates					
Carbaryl	2	1	2	1	4
Carbofuran	2	2	3	1	12

[a]Adapted from (92).

toxaphene and chlordane have a significantly different persistence and toxicity, the PEH index value is equal for both insecticides. The environmental harm coefficient is lacking in consideration of specific chemical persistence values, as all organochlorines are assumed to have the same decomposition rate. Similarly, all organophosphates and carbamates are specified with one decomposition rate. Both of these areas are improved in the environmental exposure index, since, first, a unique measure of persistence is used for each insecticide, and, second, a first-order kinetic degradation function is used in the derivation of the index to refine the estimate of the environmental exposure.

Environmental exposure index

Previously in this chapter (see page 38), a first-order kinetic degradation function was used to develop a residue function. This function by itself will not provide a useable exposure index. However, if the integral of this function is taken over the time interval between applications, the result is an estimate of the amount of insecticide material to which the environment is exposed. As an example, if two insecticides of unequal persistence are used at equal intervals and equal application rates, not only will the maximum residue level be different, but the speed of decay between applications will also differ. Using the device of the integral will then allow both variations to be adequately reflected in the index. - The solution to the integral is:

$$I = \int_0^m A \cdot \frac{1}{1-e^{\left(\frac{-\ln(2)m}{h}\right)}} \cdot e^{\left(\frac{-\ln(2)t}{h}\right)} dt$$

$$= A \cdot \frac{1}{1-e^{\left(\frac{-\ln(2)m}{h}\right)}} \int_0^m e^{\left(\frac{-\ln(2)t}{h}\right)} dt$$

$$= A \cdot \frac{1}{1-e^{\left(\frac{-\ln(2)m}{h}\right)}} \cdot \frac{1}{\frac{-\ln(2)}{h}} \cdot \left(e^{\left(\frac{-\ln(2)m}{h}\right)} - 1\right)$$

$$= \frac{A \cdot h}{\ln(2)}$$

where I = value of the integral;

m = time period between insecticide application, in years;

A = periodic insecticide application rate;

h = half-life of the insecticide, in years;

t = time elapsed since the last application, in years.

This integral value in itself does not indicate the seriousness to the environment of the particular level of residues of the insecticide. However, the toxicity data provide precisely this kind of information. The value of the integral provides an estimate which could be denominated in "insecticide pound-days." Dividing this value by the toxicity to a particular nontarget species yields an estimate of the maximum number of this species which could be killed by the insecticide residue over the course of the entire year. Rats were chosen as the non-target species for this index, with the toxicity expressed as the lethal dose to 50 percent of test animals from acute poisoning, stated in mg per kg.

The environmental exposure index is defined to be:

$$\text{EEI} = \sum_i \frac{h_i \cdot A_i}{\ln 2 \cdot LD_i}$$

where i = 1 to 13 insecticides actually applied.

The actual value of the index as input into the linear programming model accounts for the multiple use methods for each insecticide, as well as the various crop rotation, land class, tillage method, and conservation method combinations in the model. For example, in those cases where a different chemical persistence would be encountered under two different tillage methods, the appropriate persistence is used in the model. These cases are identified in Table 8 which specifies the index parameters and values. The chemical half-life data were synthesized from numerous sources. The literature review and assumptions used in the estimation of the half-lives are listed in Appendix B.

The appropriate index value is specified in each of the model's crop production activities. By summing the index values over all production activities, a measure of the environmental exposure to insecticides can be obtained. The comparison of this measure for

Table 8. Environmental exposure index

Insecticide	Half-life years	Application rate[a]	Toxicity to rats[b]	Index (x1,000)
Organochlorines				
Chlordane, conv. till	1.10	2.0	335	9.474
Chlordane, min. till	1.30	2.0	335	11.197
Heptachlor, conv. till	1.70	1.0	90	27.251
Heptachlor, min. till	2.00	1.0	90	32.060
Toxaphene	.115	2.0	69	4.809
Organophosphates				
Diazinon, upland soils	.058	1.0	76	1.101
Diazinon, bottomland soils	.077	1.0	76	1.462
EPN	.192	0.4	4	34.625
Ethoprop	.077	1.0	61.5	1.806
Fensulfothion	.058	1.0	2	41.838
Fonofos	.077	1.0	8	13.886
Phorate, not incorporated	.019	1.0	1	27.411
Phorate, incorporated	.077	1.0	1	111.088
Terbufos	.115	1.0	4[c]	41.477
Trichlorfon	.014	1.0	275	0.072
Carbamates				
Carbaryl	.011	1.0	500	0.032
Carbofuran, 1st year corn	.115	2.5	8	51.847
Carbofuran, other corn	.115	1.0	8	20.739

[a]In pounds actual ingredients per acre. Source: (76).

[b]Acute oral LD_{50} expressed in mg/kg. Source: (82).

[c]Acute oral LD_{50} expressed in mg/kg. Source: (13).

different solutions which are based on varying environmental strategies will yield information on the environmental effects of these strategies.

CHAPTER IV. DESCRIPTION OF THE MODEL

The questions raised by the study objectives can be answered only by use of an abstraction such as a mathematical programming model, since an actual experiment cannot reasonably be run on a research plot as large as the present study area. Such an abstraction requires a number of basic assumptions to be made before a model can be used. Foremost among these is the assumption that the physical processes of the environmental system can be given a mathematical representation, e.g., an equation form. For example, one must assume that the insect damage to crops can be quantified, in terms of a probability function with an expected mean damage if the insect pests are not adequately controlled. Modeling also requires that an objective function of the system can be specified, in other words that a valuation of various possible outcomes is available such that the most desirable outcome will be easily discernible.

Given that both of these assumptions are satisfied, a model may be utilized to systematically evaluate the range of alternatives. There are several available systems which can be used in this modeling process. Of these, linear programming is the best method to analyze the complex interactions implied by the study objectives, since other methods do not allow for the same level of detail with an equivalent computational ease. "Linear programming is a computational method to determine the best plan or course of action, among many which are possible, when there are many alternatives for the plan, a specific or numerical objective exists for it, and the means or resources available for attaining it are limited" (1, p. 26). There are three components to the linear programming model: an objective function, the restraints which typically take the form of limited amounts of resources, and a large number of alternative combinations of these resources in production processes.

A linear programming model may be written in a general form as:

$$\text{maximize } Z = \sum_{j=1}^{n} c_j x_j$$

$$\text{subject to} \sum_{j=1}^{n} a_{ij} x_j \leq b_i$$

$$x_j \geq 0$$

where i = 1, 2...m.

In this specification, the c_j *represent the objective function* values for each of the n activities, and the x_j are their levels of activity. The a_{ij} represent the requirements of resource i required per unit of activity j, while the b_i denote the resource availabilities of the m resources.

Of course, the objective may be to minimize a set of costs, as it is in the study model. Similarly, one or more of the m restraints may require that a particular b_i be exceeded, such as a minimum crop output restraint. In either case, taking the negative of the particular function will conform to the above specification without changing the optimal solution.

In the present model, the chosen objective was to minimize the monetary production cost of the required level of field crop production in the study area. The restraints include land availability, limits on cropping patterns due to agronomic considerations, and minima on crop output expected from the study area. A large number of production alternatives were specified, differentiated by such characteristics as tillage methods, soil conservation methods, crop rotations, and the like. These production alternatives are described first, followed by a discussion of the restraints imposed upon the model.

Model Activities

The majority of the activities in the model are the crop producing activities, as they constitute 570 of the 1075 vectors of the model. There are many possible production methods by which the desired crop output may be raised. This model was designed to include those feasible production vectors which are of interest in the context of the study. The other model vectors include such activities as input purchases, insecticide application, terrace construction, and transfer vectors.

Crop production alternatives

Crop production alternatives were defined for each of the 9 SRG aggregates stratified by crop rotations, tillage method, and soil conservation practices. The model is concerned with the four major field crops found in the study area, namely corn, soybeans, oats, and hay or meadow.[1] These crops were combined into several crop rotations, specifically corn-soybeans (CB), corn-soybeans-oats-meadow (CBOM), corn-soybeans-oats-meadow-meadow (CBOMM), corn-oats-meadow (COM), and corn-oats-meadow-meadow (COMM). In addition, the alternatives of continuous corn (C) and cropland pasture (M) were included. This specification allows the model to combine the rotations linearly to give other rotations not specifically included. For example, if the optimal rotation were corn-corn-corn-soybeans, it would be designated in the model by one-half unit of the corn-soybeans rotations and one-half unit of continuous corn.

The tillage practices used in the model were conventional tillage fall plowed, conventional tillage spring plowed, rotary-till plant, and no-till plant. Conventional tillage is defined as the practice of moldboard plowing followed by other tillage operations. All plant residue is assumed to be covered with soil. Rotary-till plant is defined to represent the practice of combining tillage and planting in one operation as in a buffalo-till planter. This alternative is assumed to leave 66 percent of the plant residue exposed. No-till plant is defined to eliminate all tillage except for fluted coulters.

Several soil conservation methods are available for reducing erosion. The most effective method is terracing, which divides a

---

[1]Corn silage was considered to be a different commodity than corn grain only for harvesting purposes. The growing activities of both were identical.

tillable slope into several shorter slopes. Consequently, the runoff water is slowed and its erosive capability is reduced. The model included terrace construction activities specific to each SRG. These activities will be discussed in detail in a separate section below.

An additional conservation method that could be employed to reduce erosion is the practice of contouring. This method uses a field layout such that all tillage is done on the contour. As a result, the crop rows act as barriers to the runoff water, slowing it and substantially reducing the amount of soil detached by the water. Due to the field layout, some point rows may occur. These point rows will increase the labor and machinery requirement, since more time will be required for the tillage operations. The size of this increase was assumed to vary directly with the soil slope, i.e., steeper slopes will have a higher increase. The assumption was made that contouring would not be used on any land with slope less than three percent (i.e., SRG aggregates C and E).

In addition to these two conservation methods, crop tillage may be done without regard to field slopes. This "up-and-down" or "straight-row" tillage is the most erosive of the three alternatives, but its costs are lowest.

The costs for each of the production activities were computed from several basic sources (4, 5, 6, 7, 23, 44, 81, 89). The levels of the various inputs were determined separately for each alternative, and the costs of these inputs were then aggregated to arrive at the total production cost for each activity. This method is detailed in the following discussion.

Machinery costs   A first step in the computation of machinery costs was to delineate all of the machines which could potentially be used in any of the production alternatives. Different sizes of many machines are available. In these cases, a machine size was chosen which was best fitted to the assumed size of the farm operation. Census data (87) weighted for the six counties included in the study area suggested an average farm size of 269 acres in the study area. The machinery and tractor sizes were selected based on this farm size with sufficient capacity to complete the field work within the optimal time periods. For all of these machines, a purchase price, expected repair cost per hours of use, and expected useable life were ascertained (4, 5, 7, 44). Since the useable life is a function of the level of yearly use, the useful life was specified for three levels of use, corresponding to a heavy, medium, and light yearly use depending on the frequency of use of the machine in the crop rotation. The fixed costs for each of the machines and each of the three levels of use were then computed. A straight-line depreciation was assumed over the useful life of the implement with a salvage value determined by the type of machine and length of its use (4, 5). The annual cost for taxes and insurance was assumed to be two percent of the initial cost (4). An annualized average interest cost was computed at eight percent per annum on the amount of the investment over the useful life of the machine.

The cost of repairs is the only relevant variable cost for machinery. Since the repair cost is a linear function of the hours of yearly use, the latter figure had to be determined. The hours of yearly use are a function of the per acre requirement for each of the operations specific to that machine (7, 23). In the case of a rotation where each part of the rotation uses that particular machine, the per acre requirement is multiplied by 269 acres to arrive at the total yearly use figure. If the machine is used only on part of the rotation acres, the requirement is adjusted accordingly. The repair cost per 100 hours of use is computed as a varying percentage of the machine list price, depending on the machine type (4).

Tractor costs The costs for the tractor were computed similarly to the cost for machinery. The total hours of tractor use for each production alternative were assumed to equal 110 percent of the sum of the machinery time requirements for that alternative to account for idling time and travel to and from fields. The economic life of the tractor was assumed to be a function of the yearly level of use, with five categories of use ranging from less than 400 hours/year on CB no-till to just over 900 hours/year on COMM conventional spring-plow.

Fuel costs The fuel requirements for the tractor and the harvesting equipment were computed based on the total hours of use. The fuel costs were not added to the production costs directly, since a separate fuel purchase activity was used. This method would allow obtaining a number of solutions to the model with varying prices for fuel.

Labor costs The labor requirement was assumed to be equal to the tractor hour requirement plus an overhead requirement. This overhead requirement was designed to account for fixed time requirements to purchase production inputs, sell the crop outputs, and other time used to manage the farm business. It was assumed to be 15 percent of the tractor hour requirement average of all production alternatives.

Fertilizer costs The fertilizer costs were synthesized from several sources. Fertilizer recommendations were not available on an SRG basis, but rather only on a soil series basis. Soil series are large aggregates which may include soils on slopes which vary significantly. Since yield expectations on varying slopes within a soil series may also vary, the optimal fertilizer application in each case will differ. A higher soil slope was assumed to have slightly lower crop yields and thus require a lower fertilizer input for economically optimal use of resources.[1] The soil series fertilizer requirements, as broken down according to slope class, were combined into a weighted average fertilizer requirement for each SRG.

The resulting rates were adjusted further downwards since not all crop acres are fertilized; the adjustment factors were taken from Census data (87). In the computation of the fertilizer cost for rotations including meadow or soybeans, a fertilizer credit was given for the nitrogen carry-over produced by the legume. A further assumption regarding the form of nitrogen should be pointed out, namely that nitrogen was assumed to be in NH_3 form on all conventionally tilled

---

[1]The breakdown of soil series acreages by slope classes for the study area was obtained from data supplied by Dr. Highland (41). The adjustments in fertilizer recommendations by soil slope were suggested by Dr. R. Voss (90).

alternatives and in granular form on the reduced-till alternatives. Each of these forms gave a different price to the nitrogen input.

Herbicide costs The computation of the herbicide costs had to incorporate certain agronomic considerations. First, if the rotation included soybeans, the preceding corn could not be treated with atrazine to avoid carry-over problems. Second, the tillage method influenced the choice of chemical; for example, on no-till, Paraquat or a mixture including Paraquat is commonly employed, which would not be used with other tillage methods. Third, a higher than average soil organic matter content will require an increased amount of herbicide. Consequently, the SRG aggregates were grouped according to soil organic matter content in the herbicide cost computations.[1]

Drying costs It was assumed that corn was the only crop which required crop drying. The amount of corn produced by each crop rotation was multiplied by a drying cost per bushel to arrive at the total drying cost for that particular crop rotation.

Seed costs The seed costs were computed separately for each production activity. The assumption was made that the seed mortality would be higher on reduced-tilled ground than on conventional-tilled ground. The computations were based on a highly productive soil, and the costs were reduced slightly on less productive SRG aggregates.

---

[1]SRG aggregates B, G, H, I, and K have light organic matter (O.M.) content; aggregates A, C, and F have medium O.M.; and E has heavy O.M. content.

Interest costs Interest costs accrue to the production activities from two major sources: interest on long-term investments, such as machinery, and short-term production items, such as fertilizer. The interest costs on long-term investments are included in the budgets already (see the discussion on machinery and tractor costs), so that only the interest cost on short-term production items is included here. These items are fertilizer, seed, herbicide, and harvest labor (particularly on hay harvesting). Since these inputs are employed for different time periods, interest is charged for the fertilizer and seed investment for a period of eight months, for the herbicide investment for six months, and for the harvesting labor for only two months. The interest costs on the insecticide and fuel purchases are included in their purchase vectors for periods of six and five months, respectively.

Other activities

Purchase activities The model includes four relaxer activities (BY_s). These activities allow purchase of any of the four crops from regions outside the study area should the restraints of the model preclude production of any crop at the desired level.[1] These purchase activities were not likely to occur in the optimal solution unless absolutely necessary, since the crop purchase cost was set at a level 100 times the current market price.[2]

Other purchase activities were specified for certain inputs. The use of inputs such as fertilizers, seed, machinery, and the like was

[1]No purchase activity was included for corn silage.

[2]In fact, they did not enter any solution.

assumed to be fixed for each crop production activity and the costs of these inputs are reflected in the costs of each production vector. Since one objective of the study is to assess the effect of restrictions on specific insecticides, separate purchase vectors were designed for each insecticide. One of the uses of this model which is not reported here was for a study of the effect of changes in the price of fuel on production costs; this was done by parameterizing the objective function value of the fuel purchase activity.

Insecticide use The corn yields were specified in the crop production vectors on the assumption that no insecticides were applied. The potential insect problems and the amount of yield lost to insects were estimated on the basis of the specific soil, rotation, and tillage information for each production activity (76). The corollary to this estimate is, of course, the marginal productivity of each insecticide. Therefore, the insecticide use vectors of the model increase crop yields by an amount specific to each insecticide use situation. Any of the insecticides may have a different marginal productivity in different soil-tillage-rotation combinations, and a separate insecticide use vector was used in each applicable situation.

Terrace construction These activities simulated the construction of terraces on cropland. Due to the nature of the bottom land SRGs (C and E) no terrace construction activities were included on these soils. Terracing was also not allowed on those soils which could not support such a practice due to shallowness of the topsoil. In all other situations, the terrace construction activity uses one acre of unterraced land and generates one acre of terraced land, i.e., increases the terraced acreage for the SRG by one acre.

On certain SRGs, the soil slopes required use of grassed backslope terraces, that is, terraces on which the steep banks of the terrace were withdrawn from row crop production and were permanently planted to grasses. The amount of land lost from row crop production was a function of the steepness of the soil; on the steepest soils it amounted to as much as 10 percent.[1] The crop growing activities on these terraced acres were adjusted for this loss of tilled acreage; thus, for example, one acre of terraced land on SRG aggregate A could produce 0.9 acres of row crops.

The terrace construction costs were computed on the basis of Soil Conservation Service specifications (85). The recommended terrace spacing was determined based on the Soil Conservation Service specifications and the relevant soil data. The terracing costs, including the costs for earth work, intakes, the outlets and a limited amount of topsoiling, were computed separately for each SRG aggregate by SCS personnel (64).

Objective Function and Model Restraints

The specific functions included in the study model are listed below. The objective function specified that the optimal solution to the model will minimize the total production costs, including terrace construction costs and other input purchase costs.

[1]The terrace specifications were computed from Soil Conservation Service recommendations (85).

Objective Function:

Minimize

$$Z = \sum_i \sum_j \sum_k \sum_m PA_{ijkm} \cdot PC_{ijkm} + \sum_i \sum_j \sum_k \sum_n \sum_p \sum_r IA_{ijknpr} \cdot IC_{ijknpr} +$$

$$\sum_n IP_n \cdot IC_n + \sum_i \sum_j \sum_k \sum_m FG_{ijkm} \cdot FC + \sum_i TB_i \cdot TC_i +$$

$$\sum_i SIL_i \cdot CSIL_i + \sum_s BY_s \cdot BC_s$$

i = 1 to 9 SRG aggregates
j = 1 to 6 crop rotations
k = 1 to 4 tillage methods
m = 1 to 3 conservation methods
n = 1 to 13 insecticides
p = 1 to 2 insecticide use periods
r = 1 to 3 insect problem complexes
s = 1 to 5 crops

where

PA_{ijkm} = acres of rotation j on SRG i with tillage method k and conservation method m.

PC_{ijkm} = cost of producing one acre of rotation j on SRG i with tillage method k and conservation method m.

IA_{ijknpr} = acres of use of insecticide n against insect problem complex r in use period p in rotation j on SRG i with tillage method k.

IC_{ijknpr} = application cost per acre of use of insecticide n against insect problem complex r in use period p in rotation j on SRG i with tillage method k.

IP_n = pounds of use of insecticide n.

IC_n = cost per pound of insecticide n.

FG_{ijkm} = fuel gallons required to grow one acre of rotation j on SRG i with tillage method k and conservation method m.

FC = price per gallon of fuel.

TB_i = acres of terraces constructed on SRG i.

TC_i = construction cost per acre of terrace constructed on SRG i.

SIL_i = acres of corn harvested as silage on SRG i.

$CSIL_i$ = cost of harvesting one acre of corn as silage on SRG i.

BY_s = purchase one unit of crop s.

BC_s = purchase cost per unit of crop s.

Separate land restraints are specified for terraced and unterraced land for each SRG aggregate. The two bottom land SRGs (C and E) were assumed not to have any terraced land, since these SRGs have slopes of less than two percent; thus, only an unterraced land restraint is included for SRGs C and E. Consequently, no terrace construction activities were specified for SRGs C and E.

Land restraint by SRG aggregate:

$$\sum_i \sum_k \sum_m PA_{ijkm} + PAS_i + TB_i \leq LAND_i$$

i = 1 to 9 SRG aggregates
j = 1 to 6 crop rotations
k = 1 to 4 tillage methods
m = 1 to 2 conservation methods (excluding terracing)

where PAS_i = permanent pasture acreage on SRG aggregate i.

$LAND_i$ = nonterraced land available for SRG aggregate i.

Terraced land restraint by SRG aggregate:

$$\sum_i \sum_k \sum_m PA_{ijkm} + PAST_i - TB_i \leq TERL_i$$

i = 1 to 9 SRG aggregates
j = 1 to 6 crop rotations
k = 1 to 4 tillage methods
m = 3 terracing

where $PAST_i$ = permanent pasture on terraced land in SRG aggregate i.

$TERL_i$ = terraced land available for SRG aggregate i.

Crop output demands were specified separately for each of the five crops in the model. The demands could be met either by the crop producing activities or by crop purchases.[1] The demands represented minimum levels of crop production which were computed as an interpolation of the actual crop output which was obtained during the 1967 base period and the OBERS E' projections for 1980 (88). The OBERS E' projections for the state of Iowa were prorated to the study area in the proportion of the 1967 study area output to the 1967 Iowa total output. Thus, the study area share of the state output was fixed at the 1967 level.

The crop yields were estimated for each SRG and rotation, tillage, and conservation method combination. The variation in crop yields by SRG were derived by Rosenberry et al. (70). The row crop yields for fall conventional tilled activities were assumed equal to their spring plowed counterparts. The row crop yields for the reduced tillage alternatives were reduced slightly below the conventional tilled yields.

[1]Due to the nature of the commodity, no purchase activities were specified for corn silage.

Crop output demands by crop:

a) corn grain, s = 1

$$\sum_i \sum_j \sum_k \sum_m PA_{ijkm} \cdot Y_{ijkms} - \sum_i \sum_j \sum_k \sum_m SIL_{ijkm} \cdot Y_{ijkms} +$$

$$\sum_i \sum_j \sum_k \sum_n \sum_p IY_{ijknps} \cdot IA_{ijknp} + BY_s \geq COR_s$$

b) corn silage, s = 2

$$\sum_i \sum_j \sum_k \sum_m SIL_{ijkm} \cdot CONV_i \geq COR_s$$

c) oats, s = 3

$$\sum_i \sum_j \sum_k \sum_m PA_{ijkm} \cdot Y_{ijkms} + BY_s \geq COR_s$$

d) soybeans, s = 4

$$\sum_i \sum_j \sum_k \sum_m PA_{ijkm} \cdot Y_{ijkms} + BY_s \geq COR_s$$

e) hay, s = 5

$$\sum_i \sum_j \sum_k \sum_m PA_{ijkm} \cdot Y_{ijkms} + PAS_i \cdot Y_{PAS_i} + PAST_i \cdot Y_{PAST_i} + B_s \geq COR_s$$

i = 1 to 9 SRG aggregates
j = 1 to 6 crop rotations
k = 1 to 4 tillage methods
m = 1 to 3 conservation methods
n = 1 to 13 insecticides
p = 1 to 2 insecticide use periods

where Y_{ijkms} = yield of crop s in rotation j on SRG aggregate i with tillage method k and conservation method m.

COR_s = crop output demand of crop s.

$CONV_i$ = conversion factor between corn grain yield and corn silage yield on SRG_j.

IY_{ijknps} = per acre marginal product of insecticide n used in insecticide use period p on crop s on SRG i on rotation j with tillage method k.

Each crop rotation has a unique set of associated insect problems and thus requires a unique set of insecticides. Thus, the following insecticide requirement equations were specified separately for each rotation and insect problem. Not all 13 insecticides may be present within each equation, since a particular insecticide may provide ineffective treatment for a specific insect problem.

Insecticide requirements by rotation and insect problem:

$$\sum_i \sum_k \sum_m PA_{ijkm} \cdot IR_{ijkmr} - \sum_i \sum_k \sum_n \sum_p IA_{ijknpr} \leq 0$$

i = 1 to 9 SRG aggregates
j = 1 to 6 crop rotations
k = 1 to 4 tillage methods
m = 1 to 3 conservation methods
n = 1 to 13 insecticides
p = 1 to 2 insecticide use periods
r = 1 to 3 insect problem complexes

where IR_{ijkmr} = incidence of insect problem complex r on SRG i in rotation j with tillage method k and conservation method m.

The following equations were simple inventory equations, i.e., they specified that use of the input cannot exceed availability. The fuel restraint was expressed in gallons of diesel.

Insecticide inventory:

$$\sum_i \sum_j \sum_k \sum_p \sum_r IA_{ijknpr} \cdot IU_{ijknpr} - IP_n \leq 0$$

i = 1 to 9 SRG aggregates
j = 1 to 6 rotations
k = 1 to 4 tillage methods
p = 1 to 2 insecticide use periods
r = 1 to 3 insect problem complexes

where IP_n = quantity of insecticide n purchased.

IU_{ijknpr} = application rate of insecticide against insect problem complex r on SRG i in rotation j with tillage method k during application period p.

Fuel inventory:

$$\sum_i \sum_j \sum_k \sum_m FG_{ijkm} - FP \leq 0$$

i = 1 to 9 SRG aggregates
j = 1 to 6 crop rotations
k = 1 to 4 tillage methods
m = 1 to 3 conservation methods

where FP = quantity of fuel purchased.

The sediment equation computed the amount of sediment which will be delivered to Coralville Reservoir from the erosion (as estimated by the USLE) caused by the agricultural field crop production of the study area. The equation adds the number of tons of soil eroded by each production activity multiplied by the applicable watershed delivery ratio.

Erosion:

$$\sum_i \sum_j \sum_k \sum_m PA_{ijkm} \cdot GE_{ijkm} \cdot DR_i = M$$

i = 1 to 9 SRG aggregates
j = 1 to 6 rotations
k = 1 to 4 tillage methods
m = 1 to 3 conservation methods

where GE_{ijkm} = gross erosion per acre of rotation j on SRG i with tillage method k and conservation method m.

DR_i = weighted average delivery ratio for SRG i.

M = sediment delivered to Coralville Reservoir.

The amount of specific insecticides used is multiplied by their exposure index values and then summed to provide the overall index value.

Environmental exposure index:

$$\sum_i \sum_j \sum_k \sum_n \sum_p \sum_r IA_{ijknpr} \cdot EEI_{ijknp} = N$$

i = 1 to 9 SRG aggregates
j = 1 to 6 crop rotations
n = 1 to 13 insecticides
p = 1 to 2 insecticide use periods

where EEI_{ijknp} = environmental exposure index of insecticide n used in period p in rotation j with tillage method k on SRG i.

N = value of index.

CHAPTER V. RESULTS OF THE ANALYSIS

The model described in the previous chapter was employed to estimate the effects of several environmental policies of reductions in erosion or sedimentation and restraints on insecticide use. The model was solved for several sets of assumptions. The discussion in this chapter will examine the results of each set of solutions separately. In the discussion of the following solutions, the effects of certain policies upon the variables of the model will be examined. The solutions are identified in the discussion by an identification code, as shown in Table 9. The assumptions used for each solution are given in the discussion of each solution.

First, it was assumed that an absolute maximum on gross erosion per acre cropped would be imposed. This limit was varied from 10 to 3 tons/acre/year. This limit is essentially an enforced change in agricultural production methods prohibiting all production alternatives that generate gross erosion in excess of the standard. This set of solutions thus simulates the effects of the Iowa Conservancy Law in the study area. The administrative costs and enforcement problems of this standard are probably lowest of the alternative policies considered here. However, from the standpoint of the farmer, it is also the most restrictive and inflexible policy, as it eliminates certain potential production activities thus narrowing his field of choice.

A second set of solutions assumed the imposition of a limit on sediment delivered to Coralville Reservoir, with no limits on per acre gross erosion. The linear programming model treated the whole

Table 9. Identification of computer models used in the analysis

Model identification code	Model definitions
A	Baseline model, no environmental restraints
B.1	Limit on gross erosion to 10 tons/acre/year
B.2	Limit on gross erosion to 5 tons/acre/year
B.3	Limit on gross erosion to 3 tons/acre/year
C.1	Limit on sediment delivery to Coralville to 75% of amount of baseline solution
C.2	Limit on sediment delivery to Coralville to 50% of amount of baseline solution
C.3	Limit on sediment delivery to Coralville to 25% of amount of baseline solution
D.1	Lowered sediment delivery ratios; limit on sediment delivery to 75% of amount of baseline solution
D.2	Lowered sediment delivery ratios; limit on sediment delivery to 50% of amount of baseline solution
D.3	Lowered sediment delivery ratios; limit on sediment delivery to 25% of amount of baseline solution
D.4	Lowered sediment delivery ratios; limit on sediment delivdry to 10% of amount of baseline solution
E.1	Subsidy of $0.50/acre of row crops contoured
E.2	Subsidy of $1.00/acre of row crops contoured
E.3	Subsidy of $1.50/acre of row crops contoured

Table 9 (continued)

Model identification code	Model definitions
F.1	No limit on gross erosion; subsidy of $0.50/acre row crops contoured and 33% of terrace construction costs
F.2	No limit on gross erosion; subsidy of $1.00/acre row crops contoured and 67% of terrace construction costs
F.3	No limit on gross erosion; subsidy of $1.50/acre row crops contoured and 100% of terrace construction costs
F.4	3 tons/acre/year gross erosion limit; subsidy of $0.50/acre row crops contoured and 33 % of terrace construction costs
F.5	3 tons/acre/year gross erosion limit; subsidy of $1.00/acre row crops contoured and 67% of terrace construction costs
F.6	3 tons/acre/year gross erosion limit; subsidy of $1.50/acre row crops contoured and 100% of terrace construction costs
G.1	Environmental exposure index limited to 75% of amount of baseline solution
G.2	Environmental exposure index limited to 50% of amount of baseline solution
G.3	Environmental exposure index limited to 25% of amount of baseline solution
G.4	Environmental exposure index limited to 10% of amount of baseline solution

study area as a single farm, a factor which is particularly significant in this set of solutions. In this solution set, gross erosion on certain acres may be quite high, since only the total amount of sediment delivered to Coralville Reservoir is limited. Thus, heavy erosion on some acreages may be balanced by light erosion elsewhere, resulting in a total sediment load that still meets the standard. Since the study area actually includes more than one farm, the implication of such a situation is that the amount of permissible gross erosion would vary among farmers. Since the administration of such a program presents prohibitive problems in the present land ownership structure, this set of solutions does not represent a feasible alternative policy. One additional policy was included in this set. This policy related to mechanical restraints to sediment delivery into waterways, thus lowering the sediment delivery ratio. For example, the use of filter strips may decrease sediment loads in the rivers, as the sediment will be trapped before reaching the water system. Even this policy is questionable on the grounds that it treats the symptom only and that it does nothing to prevent loss of future crop yields on the eroding fields.

The third solution set assumed that a subsidy would be paid to farmers to help defray the costs of contouring and terracing. It costs slightly more to produce one acre of row crops if it is contoured than if tillage is straight-row without regard to field contours. This cost increase is occasioned by increased time required for tillage due to possible point rows. Also, the cost of terracing land has to be charged against crop production costs on the acreages which are involved. Thus, production costs will increase as a result of using either of these erosion-reducing practices. If a subsidy were available to help farmers to offset this cost increase, these practices may find increased acceptance and use.

In all of these solutions, no limits were imposed on insecticide use and insecticides could be used freely. This assumption was changed on two additional solution sets. One of these specified maximum limits imposed in terms of the environmental exposure index. The intent of this set of solutions was to test the index for suitability in a deterministic model such as a linear programming matrix. The other set assumed that selected insecticides would be withdrawn from the market.

Baseline Solution

In order to quantify the effect of a given policy in this model, it is necessary to estimate the situation that will obtain in the absence of any environmental restriction. This solution will be referred to as the "baseline" solution throughout this chapter (Model A). The numerical results will be presented in all subsequent tables to allow for a comparison of the baseline results with model results of environmental restraints.

This baseline solution assumed that no production restraints were imposed on any soil aggregates. This implies that the production of any particular crop rotation will be concentrated on those soil aggregates which have the comparative advantage in production of this rotation. Consequently, the production of row crops is located on the soil aggregates A, B, C, and E, while the other soil aggregates are planted primarily to permanent pasture. The two bottom land soil aggregates (C and E) have crop yield limitations due to problems of soil wetness; these two aggregates are therefore not the locations of first choice for the row crops. In this solution, the bottom land areas are planted to extensive rotations, so that only about one-quarter of the bottom land acreage is planted to row crops.

The results of the baseline solution show that all tillage would use the lowest cost alternative, namely conventional till fall-plowed with no contouring. Since the objective of the linear programming model was to minimize the production cost of a minimum level of crop outputs, the model will not choose any higher cost production alternative to a cheaper one. Consequently, no contouring entered the optimal solution. Similarly, no spring-plowing was used in the solution. Both factors differ from reality, as a significant amount of spring-plowing and a lesser amount of contouring is actually used in the study area. This difference could not be reflected in the model, as no data are available on the amount and location of these practices. This variance has a practical result as it biases the results of the baseline solution to slightly overestimate the gross erosion and sediment delivery as well as underestimate production costs of the baseline solution.

Solutions with Limits on Gross Erosion

Three solutions assumed that the gross erosion for each acre cropped had to remain below specified limits. These limits were specified in three successive solutions at 10 tons/acre/year (Model B.1), 5 tons/

acre/year (Model B.2), and 3 tons/acre/year (Model B.3), respectively. The specification of these limits had the effect of eliminating from consideration in the current model all crop production activities which would produce soil erosion in excess of the specified amount. The estimation of gross soil erosion used the method which has been described in Chapter II.

As a result of these enforced erosion limits, certain changes in the model solutions occurred. Table 10 provides a summary of selected model results for these runs and gives a comparison with the baseline solution.

The increase in production costs were substantial, particularly for the 3 tons/acre limit. These increases were caused by several factors, the largest of which was the cost increase caused by the terraces newly constructed on almost one-half of the upland acreage of the areas. No subsidy or cost-sharing program was assumed for this solution,[1] so the full impact of these costs was on the production costs. Other cost changes are attributable to the changes in crop rotations and production methods which were induced by the erosion limits. These changes will be discussed below.

The decrease in sediment delivered to the reservoir was striking. A 3 tons/acre gross erosion limit decreased the sediment amount to about 10 percent of the baseline value. However, this decrease had significant costs. From these data, it is possible to compute the cost per ton of sediment reduction. This cost increased as the erosion

---

[1]This assumption was changed for the subsidy solution presented below.

Table 10. Summary of model results assuming limits on gross erosion

Item	Model A	B.1	B.2	B.3
Production cost (1,000$)	62,626	64,212	67,911	73,139
Increase of production cost over model A, %	-	2.5	8.4	16.8
Total land cropped (1,000 A)	667	665	679	698
Additional terraces built (1,000 A)	0	0	172.6	222.5
Sediment delivered to Coralville Reservoir (1,000 tons)	1,136.6	364.5	193.6	104.5
Average gross erosion per acre (tons/acre)	20.0	6.1	3.1	1.6
Environmental exposure index	20,961.3	22,144.9	17,609.9	19,382.1

limit was tightened. From a low of \$2.05 per ton of sediment reduction for the 10/tons/acre limit the cost per ton increased to \$21.64 for the 5 tons/acre limit and reached its maximum of \$58.68 per ton as the erosion limit was tightened to 3 tons/acre.

In these solutions, the environmental exposure index was treated as a residual of the production process. This treatment implied that the index reflected changes of production patterns which were made in response to the erosion standard rather than with a target of changing insecticide use. The changes in the index were attributable to two factors, namely changes in crop rotations and in location of corn production. The insecticide requirement for rotations was lower than for continuous corn since only continuous corn was assumed to require treatment for corn rootworm (76). The other major insect problem, the first-year corn insect complex, required treatment if the rotation included at least one year of meadow. However, in terms of the EEI, the index value for the insecticide chosen by the model for use against the first-year corn insect complex was lower than that for the insecticide of choice against corn rootworm. Consequently, the net result of a diversification of crop production was a decrease in the EEI. This effect was more than offset on some solutions by another factor contributed by the location of corn production. It was assumed that corn produced on the wet soils (soil aggregates C and E) required insecticide treatment against cutworm (76). Thus, the shift of corn production to the bottom lands, ceteris paribus, did increase the EEI. In the solutions summarized in Table 10, the effect on the EEI of changes in crop location was sufficient to raise the total EEI on two of four solutions when compared to the next higher erosion restriction level. One solution (the 5 tons/acre solution) showed a marked decrease in the EEI; this solution had a major increase in rotation diversification compared to the 10 tons/acre solution.

Table 11 shows the acreages of specific tillage and conservation methods for each solution. The 10 tons/acre limit could be met on all upland acres by either contouring or spring-plowing or both. The acreage which remained fall plowed with straight-row tillage throughout the solutions was exclusively located on the bottom land soils.

The 5 tons/acre limit caused more substantial changes in tillage practices. A large portion of the newly terraced land was fall-plowed, since that was the cheapest tillage method. Additional newly terraced acreages on more erosive land were planted by no-till methods. Other large acreages were tilled by rotary-till methods and planted on the contour. The 3 tons/acre limit extended the trend towards terracing and reduced tillage, as practically all of the upland soils were tilled by reduced tillage and about one-half were terraced.

The changes in crop acreages and location of production can be examined in Table 12. The 10 tons/acre limit causes a shift of row crops from soil aggregate A to aggregates C and E, that is, towards the bottom lands. Whereas in the baseline solution the bottom lands were planted partly to oats and hay, these crops are not grown on the bottom lands under any erosion limit. In fact, the bottom lands are planted exclusively to corn and soybeans under the two most stringent erosion limits.

Table 11. Acres of specified practices for models assuming limits on gross erosion

Tillage and conservation practice	Model A	Model B.1	Model B.2	Model B.3
Fall-plow:				
Straight-row	574,533	128,186	146,767	146,767
Contour	0	220,470	0	0
Terrace	7,564	3,324	119,061	1,813
Spring-plow:				
Straight-row	0	0	0	0
Contour	0	228,666	173,400	0
Terrace	0	4,240	0	0
Total plowed	582,097	584,886	439,228	148,580
Rotary-till:				
Straight-row	0	0	0	0
Contour	0	0	104,733	68,821
Terrace	0	0	0	154,973
No-till:				
Straight-row	0	0	0	0
Contour	0	0	0	171,549
Terrace	0	0	61,132	73,354
Total reduced till	0	0	165,865	468,697

Table 12. Acres of specified crops for solutions assuming limits on gross erosion

Crop and soil aggregate		Model A	Model B.1	Model B.2	Model B.3
		(rounded to nearest 1000 acres)[a]			
Corn	A	101	59	85	123
	B	199	197	171	146
	C	12	48	57	57
	E	8	16	16	16
	F	0	0	0	b/
	G	0	0	0	0
	H	0	0	0	0
	I	0	0	0	0
	K	0	0	2	2
Total		320	320	331	345
Soybeans:	A	101	59	28	0
	B	25	27	52	77
	C	12	48	57	12
	E	8	16	16	16
	F	0	0	0	0
	G	0	0	0	0
	H	0	0	0	0
	I	0	0	0	0
	K	0 0	0	0	0
Total		145	150	153	151
Oats:	A	38	57	57	57
	B	0	0	0	0
	C	12	0	0	0
	D	8	0	0	0
	E	0	0	0	0
	F	0	0	0	b/
	G	0	0	0	0
	H	0	0	0	0
	I	0	0	0	0
Total		58	57	57	58

[a]Totals may not add due to rounding.

[b]Less than 500 acres.

Table 12 (continued)

Crop and soil aggregate		Model			
		A	B.1	B.2	B.3
		(rounded to nearest 1000 acres)[a]			
Hay & pasture:	A	38	91	96	91
	B	0	0	0	0
	C	48	0	0	0
	E	8	0	0	0
	F	32	32	32	32
	G	8	8	8	8
	H	6	6	0	6
	I	1	1	1	1
	K	2	0	0	0
Total		144	138	137	138

Solutions with Limits on Sediment Delivery

These solutions were designed to simulate the effects of two policies, specifically the imposition of an area-wide limit on sediment delivery to Coralville Reservoir and changes in sediment delivery ratios caused by use of filter strips or other mechanical devices. The delivery limit was parameterized from no decrease to a maximum of 90 percent decrease. The following discussion does not report on all solutions, as it will be limited to the most interesting features.

In the first three solutions, the sediment delivery ratio was assumed constant. The amount of sediment delivered from the study area to Coralville Reservoir was restricted to less than 75 percent (Model C.1), 50 percent (Model C.2), and 25 percent (Model C.3), respectively, of the sediment amount of the baseline solution. No limits were placed on gross erosion per acre. Thus, it is possible that the erosive row crops could be produced with an erosive tillage method, as long as this production occurred in areas with a low sediment delivery ratio.

The summary of the results of these models is provided in Table 13. The increase in production costs due to the sediment standard was small. The forced reduction in sediment delivery by 75 percent could be obtained with a production cost increase of less than four percent. The production cost increase per ton of sediment reduction was small. This cost was $0.52 to reduce sediment delivery by 25 percent, increasing to $1.12 if sediment delivery were cut in half, and increasing further

Table 13. Summary of model results assuming limits on sediment delivered

Item	Model A	C.1	C.2	C.3
Production cost (1,000$)	62,626	62,775	63,264	64,994
Increase of production cost over model A, %	-	0.2	1.0	3.8
Total land cropped (1,000 A)	667	663	661	667
Additional terraces built (1,000 A)	0	0	0	0
Sediment delivered to Coralville Reservoir (1,000 tons)	1,136.6	852.5	568.3	284.2
Average gross erosion per acre (tons/acre)	20.0	14.3	9.6	4.8
Environmental exposure index	20,961.3	20,961.3	21,401.4	18,546.6

to $2.78 if sediment delivery were reduced by 75 percent.

The large reduction in sediment delivery can be achieved without construction of new terraces, as changes in crop rotation and tillage methods suffice to reduce sediment pollution below the stated limits. These changes in crop rotations and tillage methods are identifiable from Tables 14 and 15. The major change in crop rotations is to increase the production of row crops on the bottom land soils (aggregates C and E). Simultaneously, the production of oats and hay on aggregate A increases, as the major rotation in this soil group becomes more extensive. The change in tillage methods is from straight-row fall-plowing to spring-plowing or contouring or both. In the most restrictive situation, almost all of the upland soils are tilled by spring-plowing contoured. Only the most erosive soils are planted by the contour no-till method. No new terracing is needed to meet the sediment standard; the existing terraced acres are planted by other spring-plowing or no-till under the most restrictive standard.

The erosion rates per acre cropped are not directly limited in this solution, as only the total sediment amount is restricted. Consequently, the gross erosion rate on some soils is relatively high; the erosion rate in Model C.3 for soil aggregates A and B are 6.1 and 6.4 tons/acre, respectively. This implies that the maximum erosion rate per acre will vary from soil to soil. This variation may cause substantial problems in enforcement of this policy, as compliance with each soil's specific limit may be difficult for farmers whose fields include several different soils. Rather than tailor his farming

Table 14. Acres of specified crops for models assuming limits on sediment delivery

Crop and soil aggregate		Model A	Model C.1	Model C.2	Model C.3
		(rounded to nearest 1000 acres)[a]			
Corn:	A	101	101	91	76
	B	199	199	199	177
	C	12	12	23	57
	E	8	8	8	16
	F	0	0	0	0
	G	0	0	0	0
	H	0	0	0	0
	I	0	0	0	0
	K	0	0	0	0
Total		320	320	320	326
Soybeans:	A	101	101	91	30
	B	25	25	25	47
	C	12	12	23	57
	E	8	8	8	16
	F	0	0	0	0
	G	0	0	0	0
	H	0	0	0	0
	I	0	0	0	0
	K	0	0	0	0
Total		145	145	147	151
Oats:	A	38	38	48	57
	B	0	0	0	0
	C	12	12	0	0
	D	8	8	8	0
	E	0	0	0	0
	F	0	0	0	0
	G	0	0	0	0
	H	0	0	0	0
	I	0	0	0	0
Total		58	58	56	57

[a]Totals may not add due to rounding.

[b]Less than 500 acres.

Table 14 (continued)

Crop and soil aggregate		Model A	C.1	C.2	C.3
		(rounded to nearest 1000 acres)[a]			
Hay & pasture:	A	38	38	48	114
	B	0	0	0	0
	C	48	80	68	0
	E	8	8	9	0
	F	32	0	0	0
	G	8	5	3	8
	H	6	6	6	6
	I	1	1	1	1
	K	2	2	2	2
Total		144	140	138	133

Table 15. Acres of specified practices for models assuming limits on sediment delivery

Tillage and conservation practice	Model			
	A	C.1	C.2	C.3
Fall-plow:				
Straight-row	574,533	452,399	102,746	146,767
Contour	0	52,914	389,744	0
Terrace	7,564	7,564	7,564	0
Spring-plow:				
Straight-row	0	0	0	0
Contour	0	69,220	80,648	402,985
Terrace	0	0	0	3,324
Total plowed	582,097	582,097	580,702	553,076
Rotary-till:				
Straight-row	0	0	0	0
Contour	0	0	0	0
Terrace	0	0	0	0
No-till:				
Straight-row	0	0	0	0
Contour	0	0	0	35,051
Terrace	0	0	0	4,240
Total reduced till	0	0	0	39,291

operations to meet the erosion limits of each parcel of land, an "average" production method may be chosen.

A further set of solutions (Model set D) was obtained under the assumption that the sediment delivery ratios could be changed by mechanical or cultural methods. The best example of these methods is a filter strip, i.e., a strip of untilled land along the riverbanks to trap eroding soil prior to entry into the water. Other methods include small "gully-plugs," i.e., small sediment traps in gullies or other intermittent waterways, and permanent grass cover are all intermittent watercourses. It was assumed that these methods would be sufficient to lower the sediment delivery ratio by 25 percent. No attempt was made to estimate the cost of these methods, as several important cost factors cannot be specified for as large a region as the study area. There are no available estimates on how many "gully-plugs" would be required. There are also no available estimates of the acreage of the filter strips that is needed for the specified sediment trapping efficiency. Thus, the production costs of the model do not include these program costs.

The results of these solutions are summarized in Table 16. The production cost increases over the baseline value for these solutions were modest. Only in the most severely restrained solution (D.4) did the costs increase substantially, occasioned by the construction costs of terraces on almost 160,000 acres. These solutions closely paralleled the previously discussed solutions which did not assume the change of sediment delivery ratio. This similarity can also be seen

Table 16. Summary of model results assuming changes in sediment delivery ratios

Item	Model A	D.1	D.2	D.3	D.4
Production cost (1,000 $)	62,626	62,625	62,910	64,994	71,803
Increase of production cost over model A, %	-	0	0.5	3.8	14.6
Total land cropped (1,000 A)	667	667	661	668	694
Additional terraces built (1,000 A)	0	0	0	0	157.8
Sediment delivered to Coralville Reservoir (1,000 tons)	1,136.6	1,136.6	568.3	284.2	113.7
Average gross erosion (tons/acre)	20.0	20.0	12.8	4.8	1.8
Environmental exposure index	20,961.3	20,961.3	21,705.0	18,546.6	18,624.2

in Table 17 which presents responses in tillage and conservation practices to the sediment delivery maxima in the current model.

Solutions with Subsidies

The difference in production costs between the activities employing contouring and those without contouring is due to increased machinery and labor costs for contouring. This increase is attributable to the possibility of point rows occasioned by the field contour layout. These point rows require slightly more labor and machinery time during each of the tillage operations. All other production costs are not affected by contouring.

In this set of solutions it was assumed that subsidies would be paid to offset this cost increase. Since contouring is included in the model only for those soils with slopes in excess of three percent, the subsidies were made available only to upland crop activities. The amount of subsidy was parameterized in the models at \$0.50/acre (Model E.1), \$1.00/acre (Model E.2), and \$1.50/acre (Model E.3) of row crop contoured. In those production activities where row crops are part of a crop rotation, the subsidy per unit of the activity was adjusted to maintain the same level of subsidy per acre of row crops. The model had the choice of accepting the subsidy (and to produce with contouring) or to reject the payment, i.e., to produce crops by alternative methods.

The results of the model runs as parameterized are summarized in Table 18. Since the production cost differences are generally less than \$1.00, the biggest impact may be expected to occur with a \$1.00/acre subsidy. The lowest subsidy (\$0.50/acre) was too low to offset the

Table 17. Acres of specified practices for models assuming changes in sediment delivery ratios

Tillage and conservation practice	Model				
	A	D.1	D.2	D.3	D.4
<u>Fall-plow</u>:					
Straight-row	574,533	574,532	430,366	146,767	146,767
Contour	0	0	56,370	0	0
Terrace	7,564	7,564	7,564	0	0
<u>Spring-plow</u>:					
Straight-row	0	0	0	0	0
Contour	0	0	86,570	402,985	
Terrace	0	0	0	3,324	54,702
Total plowed	582,097	582,096	580,870	553,076	201,469
<u>Rotary-till</u>:					
Straight-row	0	0	0	0	0
Contour	0	0	0	0	0
Terrace	0	0	0	0	0
<u>No-till</u>:					
Straight-row	0	0	0	0	0
Contour	0	0	0	35,051	301,945
Terrace	0	0	0	4,240	110,623
Total reduced till	0	0	0	39,291	412,568

Table 18. Summary of results of models including subsidies for contouring

Item	Model A	Model E.1	Model E.2	Model E.3
Production cost (1,000 $)	62,626	62,626	62,612	62,446
Subsidy cost (1,000 $)	0	0	168	342
Total land cropped (1,000 A)	667	667	667	667
Acres contoured (1,000 A)	0	0	168	342
Sediment delivered to Coralville Reservoir (1,000 tons)	1,136.6	1,136.6	863.2	780.1
Average gross erosion (tons/acre)	20.0	20.0	14.41	13.01
Environmental exposure index	20,961.3	20,961.3	20,961.3	20,961.3

production cost difference between straight-row and contour tillage. Consequently, the solution at this subsidy level was identical to the solution obtained in the absence of any subsidy. At higher subsidy levels, the production of row crops shifted from straight-row tillage to contour tillage. At the highest subsidy level, all upland row crop production was done with contouring. No shift in production from one soil aggregate to another was found to occur, which implies that the subsidies were not sufficient to change the comparative advantage relationship among soils.

A second set of solutions including subsidies (Model set F) was obtained under the assumption that subsidies would be paid for terrace construction as well as contouring. The terrace subsidies were expressed as percentages of the terrace construction costs specific to each soil. Three levels of subsidies were specified, namely 33 percent, 66 percent, and 100 percent of the terrace construction costs. The three levels of subsidies were compiled with either of two erosion limits, no restriction (Models F.1, F.2, and F.3) or a 3 ton/acre limit (Models F.4, F.5, and F.6). It was hypothesized that the effects of the subsidy may differ under the erosion standard compared to the unrestricted solution.

A summary of the results of several of these solutions is given in Table 19. The model solutions for the lowest subsidy levels are omitted, since they present no new information compared to their respective base solutions without subsidies, as those solutions are identical. The solutions of the baseline model including subsidy payments for contouring and terrace construction are identical to the

Table 19. Summary of results of models including subsidy payments for contouring and construction of terraces

Item	Model					
	A	F.2	F.3	B.3[a]	F.5[a]	F.6[a]
Production cost (1,000 $)	62,626	62,612	62,446	73,139	71,038	69,631
Subsidy cost (1,000 $)	0	168	342	0	2,169	6,893
Total land cropped (1,000 A)	667	667	667	698	698	698
Additional terraces built (1,000A)	0	0	0	222.5	226.6	406.9
Sediment delivered to Coralville Reservoir (1,000 tons)	1,136.6	863.2	780.1	104.5	104.3	95.2
Average gross erosion (tons/acre)	20.0	14.4	13.0	1.6	1.6	1.5
Environmental exposure index	20,961.3	20,961.3	20,961.3	19,382.1	18,746.4	18,428.8

[a] Gross erosion limited to 3/tons/acre/year.

solutions obtained if subsidy payments were given for contouring alone. Thus, the subsidies available for terrace construction were not used and no terraces were constructed in the absence of soil erosion standards. The implication is that to produce crops on terraces costs more per acre than alternative production methods, even if the terraces are constructed at no cost to the landowner. It should be reiterated that this study simulates the production process from the landowner's point of view rather than the viewpoint of society. Consequently, the value of a long-term decrease of future corn production if erosion is not controlled by activities such as terracing is not included in the model's decision framework. The results of this run specifically indicate that the construction of terraces will not result from the mere availability of a cost subsidy, but will rather depend upon some additional impetus. This impetus may take the form of social pressure upon the landowner or some more direct pressure such as an erosion standard.

The results of the model in the situation when subsidies were available and an erosion standard (3 tons/acre/year) was enforced bear out the last conclusion. In the 3 tons/acre/year model, the availability of a subsidy created additional terrace construction beyond the amount required to satisfy the 3 tons/acre/year limit. In fact, at the highest subsidy level, all row crop production occurred on terraced land, except for the acreage of row crops grown on the bottom land.

Solutions with Limits on Environmental Exposure Index

The environmental exposure index was designed as a measure of potential environmental degradation from insecticide use. The EEI could then also be used as an environmental restraint in a linear programming matrix. The restraint would specify maximum levels of the EEI which in turn would restrict the crop production vectors in use and choice of insecticides. Such a set of solutions was obtained with restrictions on the EEI of 75 percent (Model G.1), 50 percent (Model G.2), 25 percent (Model G.3), and 10 percent (Model G.4) of the baseline EEI value. Selected results of these solutions are shown in Table 20. The EEI restraint did not change crop production methods, even at the most restrictive level. The only changes that were induced by the EEI restraints were changes in the insecticides used.

As the results show, the increase in total production cost was minor. The size of this cost increase explains why no other production changes resulted from the imposition of an EEI restraint. Any change in crop location, rotation, or production methods would have created a higher production cost increase than the change to higher priced but less environmentally damaging insecticides.

In summary, the EEI restraint had the expected effect. However, the impact of this restraint depended upon the availability of insecticides which are close substitutes. Should no such substitutes exist, the effect of an EEI restraint would be much larger than was found here.

Table 20. Summary of results of imposition of a limit on the environmental exposure index

Item	Model				
	A	G.1	G.2	G.3	G.4
Production cost (1,000 $)	62,626	62,657	62,688	62,719	62,898
Increase of production cost over model A, %	--	0.05	0.10	0.15	0.43
Insecticides used (lbs.):					
Chlordane	0	0	0	0	115,549.1
Ethoprop	0	0	0	0	121,126.2
Fonofos	53,911.8	107,823.6	161,735.4	53,379.5	0
Heptachlor	57,774.6	57,774.6	57,774.6	57,774.6	0
Phorate	174,505.7	120,593.9	66,682.1	12,770.3	0
Trichlorfon	19,995.3	19,995.3	19,995.3	19,995.3	19,995.3

Solutions with Limits on Specific Insecticides

At the time when these models were formulated, the insecticides which were registered for use against insect pests of corn included heptachlor and chlordane. Recent actions of the Environmental Protection Agency indicate that these two organochlorine insecticides will no longer be available for use on corn in the near future. Thus, this model was used to estimate the potential effects of such a withdrawal.

In this model, the assumption was made that heptachlor and chlordane would be used in two situations. The first situation is against the "first-year corn insect complex" on corn following one or more years of hay or meadow. This complex includes such insect pests as wireworms, white grubs, sod webworms, billbugs, cutworms, and grape colaspis. The other situation occurs on wet soils where cutworms may be a problem even in corn which does not immediately succeed a year of hay or meadow.

In both situations, organochlorine insecticides have been used as a preventive measure. Historically, such materials as DDT and aldrin were used due to their relative low price. As these two organochlorine insecticides are no longer manufactured for use on corn, they have been replaced by heptachlor and chlordane. Should these two insecticides be cancelled or suspended for use on corn, the alternative chemical is carbofuran, a carbamate. Other insecticides are labeled for use in these situations, but their higher costs make them less attractive than carbofuran in this model.[1]

The model runs described earlier in this chapter were solved again with the added assumption that chlordane and heptachlor were withdrawn from use. In each solution, the only change of the model results was the substitution of carbofuran for the amounts of chlordane which had been used. The implication is that it is cheaper to purchase the higher-priced carbofuran than to change crop rotations or the location of corn production which would be required to prevent yield losses due to cutworm or the other insect pests of the "first year complex."

The increase in production costs was relatively small. Table 21 presents the amount and the percentage of production cost increase. Since this cost increase can be attributed solely to the corn production, the cost increase per bushel is also indicated, exclusive of the amount contributed by the corn silage production.

The effect of this substitution of insecticides upon the environmental exposure index was in the direction of increased potential environmental damage. The two organochlorines are relatively long-lived but are also relatively nontoxic, while carbofuran is very toxic, even though its half-life is short. In addition, the application rate of carbofuran is quite high at 2.5 lbs./acre. As a result, the EEI was increased for each acre of use of carbofuran substituted for chlordane and heptachlor . The amount of this increase was slight, as Table 21

---

[1]A linear programming model which minimizes production costs will never choose a higher priced input over a cheaper alternative if their marginal products are identical.

Table 21. Results of withdrawal of chlordane and heptachlor in each erosion constraint model

Model restriction	Change in production costs: Dollars	Percent	Increase per bu. of corn, dollars	Change in EEI: Amount	Percent
Baseline	633,498	1.0	0.014	110	0.5
Limits on gross erosion:					
10 tons/acre/year	1,328,638	2.1	0.032	211	1.0
5 tons/acre/year	1,429,884	2.1	0.034	211	1.2
3 tons/acre/year	1,429,907	2.0	0.034	211	1.1
Limits on sediment delivery:					
75% of baseline amount	633,498	1.0	0.014	110	0.5
50% of baseline amount	869,000	1.4	0.020	151	0.7
25% of baseline amount	1,430,005	2.2	0.034	211	1.1
Changed sediment delivery ratios with limits on sediment delivery:					
75% of baseline amount	633,498	1.0	0.014	110	0.5
50% of baseline amount	835,146	1.3	0.019	145	0.7
25% of baseline amount	1,430,005	2.2	0.034	211	1.1
10% of baseline amount	1,429,888	2.0	0.034	211	1.1

shows. The EEI difference per acre of substitution is on the order of 160 to 190 percent of the previous EEI. However, the total increase in EEI is only minor, since other chemicals are much more important contributors to the index than either the organochlorines or carbofuran.

CHAPTER VI. SUMMARY AND CONCLUSIONS

Agricultural field crop production has necessarily a very intimate interaction with the environment. The intensive production processes presently used in producing field crops can cause certain undesirable environmental by-products. These by-products may reach levels sufficiently high to cause concern about the ability of the environment to assimilate them. Two of these by-products were considered in this study, namely soil erosion and insecticide residues.

Soil erosion is an inevitable result of tilling the soil in crop production. However, soil erosion can be controlled and reduced to acceptable amounts by good management and conservation practices. Similarly, while insecticides are required in modern agricultural production, the attendant insecticide residues may cause a degradation of environmental quality. This quality loss may also be limited by specific actions, primarily by changes in the amount or kind of chemicals employed in insect control.

This study had several objectives. First, it was designed to apply existing and new analytical methods to the study of impacts of environmental policies upon agriculture. While the use of the Universal Soil Loss Fquation and sediment delivery ratios is not new in the context in which it was used here, this study employed a newly developed index to quantify environmental degradation from insecticide residues. The second major objective was to identify and quantify the effects of various policies which were designed to control pollution from either erosion or insecticide residues. The effects studied included the degree of control of the target of the policy, that is, the effectiveness of control. The economic effects considered were changes of production cost, location and methods of production, and land use in the study area. These effects were assessed for several alternative policies. The policies on erosion reduction were specific limits on gross erosion per acre cropped, limits on sediment emission from the study area, and subsidies given to adoption of crop production methods which minimize erosion. The policies on insecticide residue reduction were enforced changes to use of insecticides of low environmental damage and prohibition of specific insecticides.

The analytical method employed by this study was a linear programming model. Linear programming is a particularly helpful tool in this instance, since it relies on a methodical comparison of all alternative production methods. The optimization of a linear programming model chooses a combination of production possibilities which is optimal in terms of a quantified decision variable subject to specified restraints. The restraints included a crop output level which had to be obtained by the crop production processes of the model. Other agronomic and physical restraints were also specified.

The objective variable of this study was the production cost of the required level of crop production. This objective function was minimized, so that the model solutions represent the minimum cost production processes which are feasible under the environmental, agronomic, and crop output restraints of each model. The choice of this particular objective influenced the specific results to a certain degree. If the alternative specification of a profit maximizing objective had been used, the optimal production patterns could have been slightly different. Assuming the crop output minima had been included in a profit maximizing specification, the land area used would have been at either of two levels. If none of the production processes would have been profitable, the profit maximization solution would have been very comparable to the cost minimization solution. In the more likely case that the production processes were profitable, the optimal solutions would have used every acre of the land base in every solution, as the only capacity constraint of the model was the land availability. Despite this difference, the effects of the environmental constraints would likely have been comparable.

The first major objective of this study was to refine the specification of environmental factors in a linear programming model. This objective has been met as the erosion or sedimentation variables and the Environmental Exposure Index were found to be useful in the context of the model. Despite its usefulness, there are some limitations of this index which will require improvement before it will find use in a policy decision model. These limitations relate to one assumption underlying the index, specifically to the assumption that the acute toxicity to rats can be used as a proxy for the total environmental toxicity of the insecticides. Insecticides have acute toxicities to other warm-blooded animals (including man) and to fish which are not in all cases proportional to the toxicity to rats. Furthermore, the chronic toxicities may be as significant from a policy standpoint as the acute toxicities.[1] Consequently, it is proposed that the index be refined to include the acute and chronic toxicities to other non-target organisms besides the one used here. If such a refinement were made, the index should be a useful tool for analysis of environmental policy, as the index would then reflect the total potential environmental damage from the use of specific insecticides.

The second major objective of this study was to assess certain of the economic and physical effects generated by the imposition of specific environmental policies. These policies were designed to reduce certain kinds of pollution, i.e., to cause a withholding of certain pollutants from the environment. Several policies were specified on the two types of pollution considered in this study, namely erosion and insecticide residues.

The effects of pollution reducing policies upon the physical level of pollution were striking. While the specific effects varied among policies, each policy decreased pollution to a certain degree. The sediment generated by field crop production of the study area and delivered to Coralville Reservoir could be decreased by as much as 90 percent by imposition of an erosion standard. This decrease could be achieved while maintaining the crop output of the study area at a

---

[a]The overriding consideration from a policy standpoint may be the potential carcinogenic effect of chronic exposure to toxic chemicals. Russell Train pointed out that "continued use of these compounds constituted a cancer risk to man" (69) in commenting upon EPA's decision to institute cancellation hearings on most uses of chlordane and heptachlor.

constant level. A similar result obtained in the case of the environmental exposure index. This index could be reduced by 90 percent of its original level without adversely affecting crop production levels.

The most stringent erosion standards could be met only the the installation of terraces on a grand scale. Terraces would need to be constructed on about 50 percent of the upland acreages to meet the most stringent erosion standards. Only in the case of a 100 percent subsidy of terrace construction costs was the entire upland row crop production located on newly terraced land. While this particular solution has the lowest soil erosion level of all solutions, it represents a situation which is likely to be politically unacceptable. In addition to the political infeasibility, it also presents a demand for terrace construction which exceeds the potential or feasible amount of construction by a wide margin.

The implication of this excess demand is that it may be physically impossible for crop producers of the study area to comply with a standard of gross erosion limited to less than 5 tons/acre/year, if the present level of crop production of the region were to be maintained. Full compliance could be achieved only after all required terraces are installed; this process could take several years. Until this construction process is completed, the choice for society is to either enforce a gross erosion standard rather loosely, i.e., prohibit only particularly flagrant soil erosion, or to accept a loss of row crop production in this region.

One effect common to all environmental policies was an increase of the production costs of the study area crop output. The increases of production costs which were induced by the specific environmental standard varied from negligible to a high of 22 percent of the production costs of the baseline amount. The cost increase may vary among farms based on the particular soil mix of the farms. The model results indicate that the bottom land soils will be preferred for row crop production if an erosion constraint is imposed. Since the row crops are more profitable per acre than oats or hay, this implies a potential income shift from upland to bottom land soils. This shift, in turn, will cause land prices to change, raising the value of the erosion-free bottom lands and reducing the value of the erosive uplands. Consequently, a windfall gain or loss will be incurred by affected landowners as a result of the imposition of an erosion constraint. The model used in this study cannot adequately quantify these inter-farm transfers of wealth. However, the absence of this quantification was not intended to imply that these costs were neglibible; quite the contrary, they may be sufficient to cause changes of land ownership.

It was shown in Chapter I that the socially optimal level of pollution control can be determined by reference to marginal benefit and marginal cost functions which specify the benefit or cost for each pollution unit withheld from the environment. The cost data of the model results can be used to compute the cost per unit of reduction for either of the two pollutants considered here. These costs are presented in Tables 22 and 23. Both marginal cost curves show costs

Table 22. Marginal costs of decreasing delivery to Coralville Reservoir of sediment produced from crop tillage in the study area

Model	Sediment delivered	Sediment withheld	Changes in amount of sediment withheld	Production cost[a]	Change of production cost	Marginal cost per ton sediment withheld
	--------(1,000 tons)--------			------(1,000 $)------		($/ton)
A	1,136.6	0	-	62,626	-	-
E.2 and F.2	863.2	273.4	273.4	62,780	154	0.56
C.1	852.5	284.1	10.7	62,775	-5	-0.47
E.3 and F.3	780.1	356.5	72.4	62,788	13	0.18
C.2	568.3	568.3	211.8	63,264	476	2.25
B.1	364.5	772.1	203.8	64,212	948	4.65
C.3	284.2	852.4	80.3	64,994	782	9.74
B.2	193.6	943.0	90.6	67,911	2,917	32.20
B.3	104.5	1,032.1	89.1	73,139	5,228	58.68
F.5	104.3	1,032.2	0.2	73,207	68	340.00
F.6	95.2	1,041.4	9.1	76,524	3,317	364.50

[a]Includes subsidies if applicable.

Table 23. Marginal costs of decreasing the environmental exposure index (EEI) in crop production in the study area

Model	EEI	Change in EEI	Production cost	Change of production cost	Marginal cost per EEI unit withheld
			----(1,000 $)-----		(dollars)
A	20,961	-	62,626	-	-
G.1	15,721	5,240	62,657	31	0.006
G.2	10,480	5,240	62,688	31	0.006
G.3	5,240	5,240	62,719	31	0.006
G.4	2,096	3,144	62,898	179	0.057

which increase as the amount of pollutant withheld from the environment increases. This cost increases at an increasing rate as more pollutant is withheld.

No function is presently available which shows the marginal benefit of reductions of the two pollutants. Thus it is not possible to compute the socially optimal level of pollution reduction. The marginal benefit functions may be very difficult to estimate as they involve monetarizing several variables which have been expressed in physical terms only. For example, one benefit of a reduction in the sediment load of the Iowa River and Coralville Reservoir is a decrease in the turbidity of the water, thus potentially increasing the amount of sunlight available below the water surface. This could increase plant and algae growth in the water, leading to a potential increase of fish biomass available for harvest. The quantification of benefits may be hampered by lack of specification of the physical relationships involved, as well as the difficulty of attaching monetary values to intangible variables relating to subjective evaluations of environmental quality. Despite these difficulties, further work on this quantification should be undertaken, since that would allow for a comparison of the marginal costs and benefits of environmental policies. Such comparisons should then lead society to choosing an optimal environmental policy.

REFERENCES

1. Agrawal, R. C. and E. O. Heady. Operations Research Methods for Agricultural Decisions. Ames, Iowa: Iowa State University Press, 1972.

2. Allen, Norman, R. L. Walker, L. C. Fife, R. D. Chisholm, L. Koblitsky, J. F. Bullock, C. R. Hodge, and E. E. Hall. Persistence of BHC, DDT, and Toxaphene in Soil and the Tolerances of Certain Crops to Their Residue. U.S. Department of Agriculture Technical Bulletin No. 1090, May 1954.

3. Andrilenas, Paul A. Farmers' Use of Pesticides in 1971 ... Quantities. U.S. Department of Agriculture, Economic Research Service, Agricultural Economic Report No. 252, July 1974.

4. Ayres, George E. Estimating New Machinery Costs. Iowa State University, Cooperative Extension Service Bulletin AE1077, Jan. 1974.

5. Ayres, George E. Estimating Used Machinery Costs. Iowa State University, Cooperative Extension Service Bulletin AE1078, Jan. 1974.

6. Ayres, George E. Fuel Required for Field Operations, Iowa State University, Cooperative Extension Service Bulletin AE1079, March 1974.

7. Background Information for Use with CROP-OPT System 6th revision. Iowa State University, Cooperative Extension Service Bulletin FM1628, Nov. 1974.

8. Bailey, G. W. and J. L. White. "Factors Influencing the Adsorption, Desorption, and Movement of Pesticides in Soil." Residue Reviews 32 (1970):29-92.

9. Barthel, W. F., R. T. Murphy, W. G. Mitchell, and C. Carley. "The Fate of Heptachlor in the Soil Following Granular Application to the Surface." Journal of Agricultural and Food Chemistry 8 (1960):445.

10. Beasley, R. P. Erosion and Sediment Pollution Control. Ames, Iowa: Iowa State University Press, 1972.

11. Bess, Henry A. and J. W. Hylin. "Persistence of Termiticides in Hawaiian Soils." Journal of Economic Entomology 63 (2) (Apr. 1970):633-638.

12. Blake, Helen T. and Paul A. Andrilenas. Farmers' Use of Pesticides in 1971 ... Expenditures. U.S. Department of Agriculture, Economic Research Service, Agricultural Economic Report No. 296, Nov. 1975.

13. Blinn, Roger, American Cyanimid Co., Clarksville, N. J. Personal Communication, Nov. 20, 1975.

14. Boyce, R., U.S. Department of Agriculture, Soil Conservation Service, Hyattsville, Md. Personal communication, Sept. 10, 1974.

15. Bro-Rasmussen, F., E. Noddegaard, and K. Voldum-Clausen. "Degradation of Diazinon in Soil." Journal of the Science of Food and Agriculture 19 (May 1968):278-281.

16. Burns, R. G. "The Loss of Phosdrin and Phorate Insecticides from a Range of Soil Types." Bulletin of Environmental Contamination and Toxicology 6 (4) (1971):316-321.

17. Carlo, Caleb Pagan, D. Ashdown, and V. G. Heller. The Persistence on Parathion, Toxaphene, and Methoxychlor in Soil. Oklahoma Agricultural Experiment Station, Technical Bulletin T-42, Jan. 1952.

18. Caro, Joseph H., Horatio P. Freeman, and Banjamin C. Turner. "Persistence in Soil and Losses in Runoff of Soil-Incorporated Carbaryl in a Small Watershed." Journal of Agricultural and Food Chemistry 22 (5) (1974):860-863.

19. Caro, J. H., Horatio P. Freeman, Dwight E. Glotfelty, Benjamin C. Turner, and Williams M. Edwards. "Dissipation of Soil-Incorporated Carbofuran in the Field." Journal of Agricultural and Food Chemistry 21 (1973):1010-1015.

20. Chisholm, D. "Persistence of Fensulfothion in Soil and Uptake by Rutabagas and Carrots." Canadian Journal of Plant Science 54 (1974):667-671.

21. Chisholm, D. and A. W. MacPhee. "Persistence and Effects of Some Pesticides in Soil." Journal of Economic Entomology 65 (4) (Aug. 1972):1010-1013.

22. Code of Iowa, Section 467A and D, 1973.

23. CROP-OPT System, Iowa State University, Cooperative Extension Service FM1627, 6th revision, Nov. 1974.

24. Dixon, Orani, Peter Dixon and John Miranowski. "Insecticide Requirements in an efficient Agricultural Sector." Review of Economics and Statistics 55 (4) (1973):423-432.

25. Dougal, Merwin D. and Ronald L. Rossmiller. Annual Report of the Iowa State Water Resources Research Institute for FY 1975. Iowa State University, Iowa State Water Resources Research Institute, 1975.

26. Edwards, C. A. "Insecticide Residues in Soils." Residue Review 13 (1965):83-132.

27. Fleck, Elmer E. "Chemistry of Insecticides." In Pesticides and Their Effects on Soils and Water. Madison, WI: Soil Science Society of America, Inc., Nov. 1966.

28. Fleming, Walter E., and Warren W. Maines. "Persistence of Chlordane in Soils of the Area Infested by the Japanese Beetle." Journal of Economic Entomology 47 (1) (Feb. 1954):165-169.

29. Foster, A. C. and V. R. Boswell. Some Effects of Insecticide Spray Accumulations in Soil on Crop Plants. U.S. Department of Agriculture, Technical Bulletin No. 1149, 1956.

30. Gannon, Norman and J. H. Bigger. "The Conversion of Aldrin and Heptachlor to Their Epoxides in Soil." Journal of Economic Entomology 51 (1) (Feb. 1958):1-2.

31. Getzin, L. W. "Persistence and Degradation of Carbofuran in Soil." Environmental Entomology 2 (3) (June 1973):461-467.

32. Getzin, L. W. "Persistence of Diazinon and Zinophos in Soil: Effects of Autoclaving, Temperature, Moisture, and Acidity." Journal of Economic Entomology 61 (6) (Dec. 1968):1560-1565.

33. Getzin, L. W. and R. K. Chapman. "The Fate of Phorate in Soils." Journal of Economic Entomology 53 (1) (Feb. 1960):47-51.

34. Getzin, L. W. and I. Rosefield. "Persistence of Diazinon and Zinophos in Soils." Journal of Economic Entomology 59 (3) (June 1966):512-516.

35. Getzin, L. W. and I. Rosefield. "Organophosphorous Insecticide Degradation by Heat-Labile Substances in Soil." Journal of Agricultural and Food Chemistry 16 (4) (July-Aug. 1968):598-601.

36. Hamaker, John W. "Mathematical Prediction of Cumulative Levels of Pesticides in Soil." In Advances in Chemistry Series 60. Edited by Robert F. Gould. Washington, D. C.: American Chemical Society, 1966.

37. Harris, C. R. and J. L. Hitchon. "Laboratory Evaluation of Candidate Materials as Potential Insecticides II." Journal of Economic Entomology 63 (1) (1970):2-7.

38. Harris, C. R., A. R. Thompson, and C. M. Tu. "Insecticides and the Soil Environment." Proceedings of the Entomological Society of Ontario 102 (1971):156-168.

39. Headley, J. C. "Policies for Externalities Extending to Resources and Environment." In Externalities in the Transformation of Agriculture: Distribution of Benefits and Costs from Development. Edited by E. O. Heady and L. R. Whiting. Ames, Iowa: Iowa State Press, 1975.

40. Henriet, J. "La pollution de l'environment par les pesticides." Parasitica 30 (1) (1974):5-12. (Translation mine).

41. Highland, John D., Iowa State University, Agronomy Department. Unpublished working materials, ca. 1970.

42. Huvar, A. J., Mobil Chemical Company, Crop Chemicals Group, Richmond, VA. Personal communication, Nov. 24, 1975.

43. Iowa Department of Environmental Quality, Water Quality Management Division, Planning and Analysis Section. Water Quality Report. Des Moines, April 1975.

44. James, Sidney. Midwest Farm Planning Manual, 3rd edition. Ames, Iowa: Iowa State University Press, 1973.

45. Johnson, D. P. and H. A. Stansbury. "Adaptation of Sevin Insecticide (Carbaryl) Residue Method to Various Crops." Journal of Agricultural and Food Chemistry 13 (3) (May-June 1965):235-238.

46. Johnson, H. P. and W. C. Moldenhauer. "Pollution by Sediment Sources and the Detachment and Transport Processes." In Agricultural Practices and Water Quality. Edited by Ted L. Willrich and George E. Smith. Ames, Iowa: Iowa State University Press, 1970.

47. Kearney, P. C., R. G. Nash, and A. R. Insensee. "Persistence of Pesticide Residue in Soils." In Chemical Fallout: Current Research on Persistent Pesticides, pp. 54-67. Edited by Morton W. Miller and George G. Berg. Springfield, IL: Charles C. Thomas, 1969.

48. Kiigemagi, Ulo and L. C. Terriere. "The Persistence of Zinophos and Dyfonate in Soil." Bulletin of Environmental Contamination and Toxicology 6 (4) (1971):355-361.

49. Kiigemagi, Ulo, H. E. Morrison, J. E. Roberts, and W. B. Bollen. "Biological and Chemical Studies on the Decline of Soil Insecticides." Journal of Economic Entomology 51 (2) (Apr. 1958):198-204.

50. Kneese, Allen V. and Blair T. Bower. Managing Water Quality: Economics, Technology, Institutions. Baltimore, Md.: Johns Hopkins Press, 1968.

51. Konrad, J. G., D. E. Armstrong, and G. Chesters. "Soil Degradation of Diazinon, a Phosphorothioate Insecticide." Agronomy Journal 59 (Nov.-Dec. 1967):591-594.

52. Kuhr, R. J., A. C. Davis, and J. B. Bourke. "Dissipation of Guthion, Sevin, Polyram, Phygon and Systox from Apple Orchard Soil." Bulletin of Environmental Contamination and Toxicology 11 (3) (1974):224-230.

53. Laveglia, James G., Department of Entomology, Iowa State University, Ames, IA. Interview, October 23, 1975.

54. Laveglia, James and P. A. Dahm. "Oxidation of Terbufos (Counter) in Three Iowa Surface Soils." Environmental Entomology 4 (5) (Oct. 1975):715-718.

55. Leuck, D. B. and M. C. Bowman. "Residues of Phorate and Five of Its Metabolites: Their Persistence in Forage Corn and Grass." Journal of Economic Entomology 63 (6) (Dec. 1970):1838-1841.

56. Leuck, D. B. and M. C. Bowman. "Persistence of Residues of Dasanit and Three of Its Metabolites in Coastal Bermudagrass, Forage Corn, and Corn Silage." Journal of Economic Entomology 65 (1) (Feb. 1972): 257-260.

57. Lichtenstein, E. P. and J. B. Polivka. "Persistence of Some Chlorinated Hydrocarbon Insecticides in Turf Soils." Journal of Economic Entomology 52 (2) (Apr. 1959):289-293.

58. Lichtenstein, E. P. and K. R. Schulz. "Effect of Soil Cultivation, Soil Surface and Water on the Persistence of Insecticidal Residues in Soils." Journal of Economic Entomology 54 (3) (June 1961):517-522.

59. Lichtenstein, E. P. and K. R. Schulz. "Persistence of some Chlorinated Hydrocarbon Insecticides as Influenced by Soil Types, Rate of Application and Temperature." Journal of Economic Entomology 52 (1) (Feb. 1959):124-131.

60. Lichtenstein, E. P. and K. R. Schulz. "Residues of Aldrin and Heptachlor in Soils and Their Translocation into Various Crops." Journal of Agricultural and Food Chemistry 13 (1) (Jan.-Feb. 1965): 57-63.

61. Lichtenstein, E. P., T. W. Fuhremann., K. R. Schulz, and T. T. Liang. "Effects of Field Application Methods on the Persistence and Metabolism of Phorate in Soil and Its Translocation into Crops." Journal of Economic Entomology 66 (4) (Aug. 1973): 863-866.

62. Lichtenstein, E. P., C. H. Mueller, G. R. Myrdal, and K. R. Schulz. "Vertical Distribution and Persistence of Insecticidal Residues in Soils as Influenced by Mode of Application and a Cover Crop." Journal of Economic Entomology 55 (2) (Apr. 1962):215-219.

63. Menzie, Calvin M. "Fate of Pesticides in the Environment." Annual Review of Entomology 17 (1972):199-222.

64. Moon, Wilson T., Iowa State Conservationist, Soil Conservation Service, U.S. Department of Agriculture, Des Moines. Personal communication, June 16, 1975.

65. National Research Council, Committee on Plant and Animal Pests, Subcommittee on Insect Pests. Insect-Pest Management and Control, Volume 3 of Principles of Plant and Animal Pest Control. National Academy of Sciences, National Research Council Publication 1695, 1969.

66. Neumeyer, John L. "Pesticides." In Principles of Medicinal Chemistry. Edited by W. O. Foye. Philadelphia: Lea and Febiger. 1974.

67. Onsager, J. A. and H. W. Rusk. "Potency of the Residues of Some Nonpersistent Insecticides in Soil Against Wireworms." Journal of Economic Entomology 62 (1971):1060-1064.

68. Parker, Bruce L. and J. E. Dewey. "Decline of Phorate and Dimethoate Residues in Treated Soils Based on Toxicity to D. Melanogaster." Journal of Economic Entomology 58 (1965):106.

69. "Pesticide Benefits and Risks Stressed by Train." Environmental News R-91 (March 29, 1976):1-2.

70. Rosenberry, Paul E., Merritt Padgitt, and Priscilla Prophet. Iowa Cedar Rivers Basin Conservation Needs Inventory. U.S. Department of Agriculture, Economic Research Service, Natural Resource Economics Division, Ames, Iowa, Dec. 1973. (mimeographed)

71. Schulz, K. R. and E. P. Lichtenstein. "Field Studies on the Persistence and Movement of Dyfonate in Soil." Journal of Economic Entomology 64 (1) (Feb. 1971):283-287.

72. Schulz, K. R, E. P. Lichtenstein, T. W. Fuhremann, and T. L. Liang. "Movement and Metabolism of Phorate Under Field Conditions after Granular Band Applications." Journal of Economic Entomology 66 (4) (Aug. 1973):873-875.

73. Stetson, G. G., Chemagro Agricultural Division, Mobay Chemical Corporation, Kansas City, MO. Personal communication, Dec. 24, 1975.

74. Stevens, Lynn J., Carroll W. Collier, and Donald W. Woodham. "Monitoring Pesticides in Soil from Areas of Regular, Limited, and No Pesticide Use." Pesticides Monitoring Journal 4 (3) (Dec. 1970): 145-164.

75. Stewart, D. K. R. and C. J. S. Fox. "Persistence of Organochlorine Insectides and Their Metabolites in Nova Scotia Soils." Journal of Economic Entomology 64 (2) (Apr. 1971):367-371.

76. Stockdale, Harold J., Department of Entomology, Iowa State University, Ames, Iowa. Personal communication, 1975.

77. Suett, D. L. "Persistence and Degradation of Chlorfenvinphos, Diazinon, Fonofos and Phorate in Soils and Their Uptake by Carrots." Pesticide Science 2 (May-June):105-112.

78. Terriere, L. C. and D. W. Ingalsbe. "Translocation and Residual Action of Soil Insecticides." Journal of Economic Entomology 46 (5) (Oct. 1953):751-753.

79. Toxaphene Use Patterns and Environmental Aspects. Wilmington, Del.: Hercules Incorporated, Nov. 25, 1970.

80. U.S. Congress. Federal Water Pollution Control Act PL 92-500, 92nd Congress, 1972.

81. U.S. Department of Agriculture. Agricultureal Prices, various issues, 1975.

82. U.S. Department of Agriculture, Agricultural Research Service. Control of Water Pollution from Cropland, Volume I, Nov. 1975.

83. U.S. Department of Agriculture, Agricultural Research Service, Entomology Research Division. "Residues in Fatty Tissues, Brain, and Milk of Cattle from Insecticides Applied for Grasshopper Control on Rangeland." Journal of Economic Entomology 52 (6) (Dec. 1959):1206-1210.

84. U.S. Department of Agriculture, Iowa-Cedar Rivers Basin Field Advisory Committee. Working materials for use in Iowa-Cedar Rivers Basin Type IV Study, Main Report, Des Moines Iowa, 1972.

85. U.S. Department of Agriculture, Soil Conservation Service, Iowa. "Technical Standards and Specifications for Conservation Practices." Work Unit Technical Guide, Section 4A-Cropland, Code No. 600 and 602, Jan. 1973.

86. U.S. Department of Agriculture, Soil Conservation Service. Work Unit Technical Guide, Section III-B, April 1969.

87. U.S. Department of Commerce, Bureau of the Census. U.S. Census of Agriculture, 1969, Volume I, Statistics for the States and Counties, Iowa, 1971.

88. U.S. Water Resources Council, 1972 OBERS Projections, Series E' Population Supplement, Agricultural Supplement. Washington, D.C.: U.S. Government Printing Office, May 1975.

89. Voss, Regis D. General Guide to Fertilizer Recommendations in Iowa. Iowa State University, Cooperative Extension Bulletin AG65, (rev.), Aug. 1973.

90. Voss, Regis D., Iowa State University, Agronomy Department. Personal communication, 1975.

91. Wadleigh, Cecil H. Wastes in Relation to Agriculture and Forestry. U.S. Department of Agriculture. Misc. Publication 1065, 1968.

92. Weber, J. B. "Agricultural Chemicals and Their Importance as a Non-Point Source of Water Pollution ." In Non-Point Sources of Water Pollution. Edited by P. M. Ashton and R. C. Underwood. Blacksburg, Va.: Virginia Water Resources Research Center, Virginia Polytechnic Institute and State University, Sept. 1975.

93. Wilkinson, A. T. S., D. G. Finlayson, and H. V. Morley. "Toxic Residues in Soil 9 Years after Treatment with Aldrin and Heptachlor." Science 143 (14) (Feb. 1964):681-682.

94. Wingo, Curtis W. Persistence and Degradation of Dieldrin and Heptachlor in Soil and Effects on Plants. Missouri Agricultural Experiment Station Research Bulletin 914, 1966.

95. Wischmeyer, Walter H. "Use and Misuse of the Universal Soil Loss Equation." Journal of Soil and Water Conservation 31 (1) (Jan.-Feb. 1976):5-9.

96. Wischmeyer, Walter H. and Dwight D. Smith. Predicting Rainfall-Erosion Losses from Cropland East of the Rocky Mountains. U.S. Department of Agriculture, Agricultural Handbook 282, May 1965.

97. Young, William R. and W. A. Rawlins. "The Persistence of Heptachlor in Soils." Journal of Economic Entomology 51 (1) (Feb. 1958):11-18.

ACKNOWLEDGEMENTS

The author expresses his appreciation to Dr. Earl O. Heady, Distinguished Professor of Economics, for his guidance and education provided during my graduate study.

This study was sponsored cooperatively by the Natural Resource Economics Division, Economic Research Service, U.S. Department of Agriculture, and the Iowa Agricultural and Home Economics Experiment Station. Special appreciation is extended to Velmar Davis, John Schaub, Larry Boone, Bill Crowley, Norm Landgren, and Paul Rosenberry of the Natural Resource Economics Division for their suggestions and interest at all stages of the project.

Certain of the data used in this study were generated by the Iowa-Cedar Rivers Basin Field Advisory Committee of the U.S. Department of Agriculture. Specific appreciation is expressed to Wilson T. Moon, Bill Brune, and the members of the River Basin Party of the Soil Conservation Service, U.S. Department of Agriculture, Des Moines.

The data of Dr. Harold Stockdale, Iowa State Extension Entomologist, made the insecticide portion of this study possible, and his help is appreciated. I also wish to thank Dr. Donald Kaldor, Dr. George Ladd, and Dr. Vince Sposito for their comments on this thesis and their service on my graduate committee.

I want to thank Mary Shearer for her good work in typing this thesis.

Finally, my thanks go to my wife, Delores, and my family in words which are theirs alone.

APPENDIX A. SOIL DESCRIPTIONS

Table A.1. Soil resource group description[a]

Code	Description	LCU[b]	Distribution	Major soils	Slope	Texture class	Problems
			(percent)				
1	Deep, well to somewhat poorly drained, medium to moderately fine textured bottomland soils. Moderately to moderately slowly permeable. Fine textured lower horizons may be encountered throughout the lower portion of the profile.	I a11	58	Nodaway	Level to gently sloping 0-2%	Silt loam	Minor flooding
		I a12	42				
2	Deep, well and somewhat poorly drained, medium to moderately fine textured, some lacustrine and upland soils. Moderately to moderately slow permeable. Bedrock or gravel may be encountered deep within the profile.	I a41		Tama Downs Racine Kenyon Clinton Fayette Dubuque Muscatine Mahaska	Level to gently sloping 0-5%	Silt loam	Somewhat poorly drained
		I c11					
		I c13					
		I c14					
		I c15					
		IIEa41					
		IIEc11	43				
		IIEc13					
		IIEc14					
		IIEc15					
		I b11	24				
		I b12	5				
		IIWm82	6				
		IIEm82					
		IIEb11					
		IIWL11					
		IIEb12					

[a]Source: (84).

[b]Only LCU's with areas greater than 500 acres are shown.

Table A.1 (continued)

Code	Description	LCU	Distribution (percent)	Major soils	Slope	Texture class	Problems
3	Deep, moderately well and well drained, medium and moderately fine textured upland soils. Moderate to moderately slowly permeable. Some areas of calcareous soils are included.	IIIEa41 IIIEb12 IIIEc11 IIIEc13 IIIEc14 IIIEc15 IIIEc16	 82 16	Tama Downs Racine Ostrander Dodgeville Clinton Fayette Dubuque	Gently sloping 5-14%	Silt loam	Erosion
4	Deep, moderately well to drained, moderately fine textured upland soils. Moderately to moderately slowly permeable. Some calcareous soils are included.	IVEc11 IVEc16 IVEc14 IVed11	56 40	Tama Downs Racine Ostrander Dodgeville Clinton Fayette Dubuque	Moderately steep 14-18%	Silt loam	Erosion
6	Deep, moderately well drained, moderately fine to fine textured upland soils. Moderately slowly to slowly permeable soils, with firm to very firm subsoils.	IIEd11 IVEd21	25 75	Cresco Lindley	Sloping 5-14%	Loam	Erosion

Table A.1 (continued)

Code	Description	LCU	Distribution (percent)	Major soils	Slope	Texture class	Problems
10	Deep, somewhat poorly to poorly drained upland soils with moderately fine to very fine textured subsoils. Level. Some fine textured material over sandy substrata is included. Moderately slowly to very slowly permeable.	IIWm11 IIIWn11 IIIWn12 IIIWn61 IIWm62 IIIWn31 IIIWm11	7 29 52 	Adair Keswick	Level 0-2%	Silt loam	Wetness
12	Deep, moderatley well to somewhat poorly drained upland soils with fine textured subsoils. Very slowly permeable.	IVEe21 IVEe22	90 10	Adair Keswick	Moderately steep 9-14%	Silt loam	Erosion and seepy
13	Well to excessively drained upland soils. Includes soils shallow to bedrock or sand and gravel and deep sandy soils.	IVSh11 IVSk12	98	Sogn Hagener Chelsea	Level to sloping 0-14%	Sand	Erosion and moderately low moisture holding capacity
14	Well to somewhat poorly drained, moderately deep (24-40") medium to moderately fine textured uplands soils overlying sand and gravel or bedrock and deep moderately coarse textured soils.	IISi11 IISi12 IIEi11 IIEi12 IIEj11 IIEi21	44 46 5	Dickinson	Level to gently sloping 0-5%	Loam	Low moisture holding capacity

Table A.1 (continued)

Code	Description	LCU	Distribution (percent)	Major soils	Slope	Texture class	Problems
15	Well to somewhat poorly drained, moderately deep (24-40"), medium to moderately fine textured upland soils overlying sand and gravel or bedrock. Deep moderately coarse textured soils are included.	IIIEi11	19	Dickinson	Sloping to moderately steep 5-14%		Erosion and moderately low moisture holding capacity
		IIIEi12					
		IIIEi21	5				
		IIIEj11	57				
		IVEd12	5				
		IVEi11	6				
		IVEi21					
		IVEj12	6				
16	Deep, moderately coarse to coarse textured upland soils and medium textured soils, shallow to sand and gravel.	IIIEj12	21	Dickinson	Nearly level to sloping 2-4%	Sandy loam	Erosion and low moisture holding capacity
		IIISj11	64				
		IVSk11					
		IVEj11	8				
		IIISj12					
18	Poorly drained, medium to moderately fine textured bottomland soils. Moderately to moderately slowly permeable. May be subject to overflow.	IIWm21	94	Colo	Level to nearly level 0-2%	Silty clay loam and loam	Poorly drained and overflow
		IIWm22	6				
20	Poorly drained, medium to moderately fine textured soils of uplands or lacustrine plains. Moderately slowly permeable. (Includes moderately deep soils over bedrock and/or gravel). May be seepy. Includes some calcareous soils.	IIWm31	71	Tainter Clyde Tripoli			
		IIWm32	23				
		IIWm33					
		IIWm41	5				
		IIIWn41					
		IIWn31					

Table A.1 (continued)

Code	Description	LCU	Distribution (percent)	Major soils	Slope	Texture class	Problems
22	Organic upland and depression soils. Agricultural soils when drained.	IIIWn51	100		Level 0-2%	Muck	Wetness
23	Alluvial bottomland and organic soils subject to variable frequency of overflow and wetness	IIIWn61	7	Colo-Zook	Level 0-2%	Mixed alluvial soils	Wetness overflow
		VWP11	92				
		VIIWq11					
28	Moderately coarse to fine textured upland soils. Included are soils which are moderately deep or deep to bedrock or sand and gravel.	VIEc11	12	Downs	Hilly to steep > 14%	Silt loam and loam	Erosion and low moisture holding capacity
		VIEc14	26	Racine			
		VIEc16		Clinton			
		VIEd11		Fayette			
		VIEd12	6	Lindley			
		VIEd21	6	Keswick			
		VIEe21	6				
		VIEe22					
		VIEi11					
		VIEi21					
		VIEj11					
		VIEj12					
		VIIEa41					
		VIIEc11					
		VIIEc13					
		VIIEc14					
		VIIEc16					
		VIIEd12	20				

Table A.1 (continued).

Code	Description	LCU	Distribution (percent)	Major soils	Slope	Texture class	Problems
28 (continued)							
		VIIEe22					
		VIIEj11					
		VIIEj12	5				
		VIIEe21					
		VIIEf11					
		VIIEd21	6				
29	Well to excessively drained coarse textured and shallow soils of the uplands.	VIISk12	26	Rockton	Sloping		Erosion
		VIISh11	32	Dogerville	to steep		and low
		VISh11		Soghn	9-24%		moisture
		VISk12	35				holding capacity

APPENDIX B. INSECTICIDE PERSISTENCE DATA

This appendix reviews the literature on persistence of those insecticides which are included in this study. The insecticides will be discussed in alphabetical order within each chemical group.

Persistence data in field situations on about half the insecticides included in the present model are provided in a survey article which is based on a review of approximately eighty sources. Persistence was defined as the time required for a 75 to 100 percent loss of the pesticide. These persistence values were based on normal rates of application and normal agricultural conditions (47). Since the article did not specify whether a particular persistence value was associated with a 75 to 100 percent loss, only a range of the half-life could be computed from the data given, assuming a first-order degradation function. The following half-lives are computed in each case based on a 99 percent disappearance for the stated persistence period for the lower figure and a 75 percent disappearance for the higher figure. The half-life ranges are 0.75 years to 2.5 years for chlordane; 0.3 years to 1.0 years for heptachlor; 0.45 years to 1.5 years for heptachlor and its epoxide; 1.8 weeks to 6 weeks for diazinon; and 2 days to 1 week for phorate.

Organochlorine Insecticides

Three of the organochlorine insecticides are included in the model, namely, chlordane, heptachlor, and toxaphene. All three have a longer persistence than the other insecticides, such as the organophosphate or carbamate chemicals.

Chlordane

The persistence reports for chlordane show a particulraly wide variance in the speed of disappearance. The reported half-lives of chlordane vary from under one year to seven years. It appears that this variance is caused by different analytical recovery methods, different application and land treatment methods (incorporation into soil versus surface application), and other unspecified variables.

The shortest half-life is reported by Fleming and Maines (28). They used applications of chlordane on 83 different soils over a period of 4 years to identify the major factors influencing persistence of chlordane. The soil organic matter was found to have major significance, particularly upon the initial speed of disappearance; the chemical half-life can be computed as 1.0 years in soils of less than 1 percent organic matter and 0.75 years in soils with more than 5 percent organic matter.

A study of the persistence of chlorinated hydrocarbon insecticides in Hawaiian soils resulted in computed half-lives of chlordane of 1.3 to 1.55 years and of heptachlor (including epoxide) of 1.2 to 1.3 years. The chemicals were applied at very high rates (500 ppm) in a silty clay soil (montmorillonite clays; pH 7.2) in a field fully exposed to weathering (11).

A substantially longer half-life of chlordane is reported by Chisholm and MacPhee (21) from a field experiment extending over 17 years. The insecticide was incorporated to a depth of 15 cm immediately after application, and the plots were cropped continuously. The amount applied during 1951-53 (in three equal applications) totaled 33.6 kg/ha (10 lbs./A/year) actual ingredient chlordane, of which 15 percent remained in 1968. Using a 16 year midpoint period, the associated half-life is 5.8 years.

Surface applications of chlordane to grassland which remained undisturbed throughout the experiment resulted in residues after 12 years of 18 percent to 30 percent of the amount applied. After 13 years on a different soil, a residue level of 26 percent was recorded. The associated half-lives are 4.8 years to 6.9 years and 6.7 years, respectively (75).

Chlordane was surface-applied to several turf soils which remained undisturbed throughout the length of the experiment. After 12 years, a residue of 12 to 15 percent of the amount applied was reported, depending on the analytical recovery method employed (57). The associated half-lives are 3.9 to 4.4 years, respectively.

A survey article by Edwards (26) states that, on the average, 55 percent of the amount of chlordane applied remains in the soil. The regression used for this prediction was based on what Edwards called "all available data." The associated half-life of chlordane is 1.1 years. This half-life is consistent with a separate estimate in the same source that three to five years is the time span during which 95 percent of the chlordane will disappear.

Edwards' estimate was adopted for use in the model. However, chlordane is quite volatile, and any soil disturbance will increase its speed of disappearance. Conversely, chlordane may be assumed to persist longer if there is no crop cultivation after pesticide application than otherwise. Since the minimum-till activities include a reduced level of crop cultivation, the judgment was made that chlordane would persist longer on minimum tilled than on conventional tilled soil. Thus, the half-life of chlordane was assumed to be 1.1 years in a conventional tilled and 1.3 years in a minimum-tilled activity.

Heptachlor

The half-life of heptachlor is reported in the literature variously as low as 0.9 years and as high as 3 years. Part of the variation can be explained by the inclusion or exclusion in the residue amount of the primary degradation product, heptachlor epoxide. Heptachlor epoxide was reported to be insecticidally active, in fact being more toxic than the parent compound, as well as more residual than heptachlor itself (30). The gradual conversion to the epoxide follows a rapid initial loss of the parent compound, probably due to volatilization (9).

Kiigemagi et al. (49) report that soil physical and chemical composition had no significant influence upon the half-life of heptachlor, but that temperature did. However, it was left unclear whether temperature influenced chemical breakdown directly or whether a higher temperature caused more volatilization.

An experiment to measure the influence of the method of insecticide application, specifically sprayed onto the soil surface only compared to incorporating the chemical into the top 5 inches of soil, found that persistence varied by a factor of 10, with the shorter persistence reported for the surface spray due to volatilization. The authors indicated that volatilization was a significant pathway for pesticide loss also for the chemical in the top inch of soil in the incorporated treatment (62). The conclusion that heptachlor will persist longer if incorporated into soil was also reported by a different study. This study of heptachlor incorporated into field plots listed a residue level after 21 months of 26 percent of the amount present after treatment (97). Such a residue level would imply a half-life of 0.9 years for heptachlor.

A long-term experiment to determine the disappearance of heptachlor from a typical Missouri soil found a half-life of 1.7 to 1.85 years. This computation is based on the total residue level, and thus the half-life includes the time required for degradation of the heptachlor epoxide as well. The parent compound by itself had an apparent half-life of about 1 year (94).

A slightly longer half-life was reported from a field experiment at Agassiz, British Columbia. Here heptachlor was applied at 5.6 kg/ha and immediately incorporated to a depth of 15 cm. The plots were tilled yearly for crop production. After nine years, about 7 percent of the applied chemical remained in the soil, practically all as the epoxide (93). This residue level implies a half-life for heptachlor (including its epoxide) of 2.3 years.

A laboratory experiment reported a very short half-life of 56 days for heptachlor incubated in shallow Pyrex dishes at a constant temperature of 26°C. The degradation was found to be closely related to temperature, since other treatments held at 46°C degraded almost completely within 56 days, with a residue of less than 2 percent of initial recovery. A treatment held at 7°C showed a residue level of 70 percent of initial recovery, while no insecticide was lost in frozen soil (59). The experiment measured only the amount of heptachlor remaining; if the epoxide had been measured, the residue levels would have been higher. Another limitation of this study is the laboratory environment, since the conditions for volatilization are different for material in a shallow dish at controlled temperature and material in a field at varying temperature.

In an experiment where the residues of heptachlor were measured for several years after a single application of 25 lbs./A, it was found that the residues (including the epoxide) decreased by 34 percent annually. Assuming a first order degradation, such a decrease implies a half-life of 5/3 years. This study also reported a longer persistence of heptachlor in alfalfa covered fields, which was attributed to a reduction in volatilization since the alfalfa field was not tilled while the other plot had been (60). This conclusion is supported by a different study which reported nearly three times as much heptachlor residue in alfalfa-covered soils than in fallowed soils 2 1/2 years after application (62).

A series of long-term experiments evaluated surface applications of several organochlorine insecticides to grassland. The plots were left entirely undisturbed for the length of the study. The amount of heptachlor residue (all as epoxide) remaining after 9 years ranged from 13 to 4 percent, reportedly associated with the soil clay content, where the soils with higher clay content had the lowest heptachlor residues (75). The associated half-lives ranged from 3.0 years to just under 2 years.

A survey article by Edwards (26) used "all available data" for a regression estimate of a half-life of heptachlor of 0.87 years. No report was made of heptachlor epoxide.

In order to include the toxic epoxide in the consideration, a half-life of 1.7 years for the heptachlor and heptachlor epoxide complex was assumed in the model for use in conventional tillage and 2.0 years for minimum tillage activities.

Toxaphene

Degradation studies on toxaphene are relatively few in number, despite the importance of toxaphene and its use over many years. There are some laboratory studies, such as one by Carlo et al. (17) which reports that toxaphene degrades substantially faster in basic soil (pH 7.8) than in acid or neutral soil. However, the experimental design does not allow for an immediate transfer of the laboratory results to a field application situation.

A relatively long half-life is reported from an experiment where toxaphene was applied annually at 20 lbs./A for four years. The insecticide was incorporated into the top six inches of soil, and the plots were cropped normally. One year after the last application, a residue amount equal to 55 percent of the total application was found (2). Such a residue level is consistent with a toxaphene half-life of 2.7 years, assuming a first-order kinetic degradation function.

A similar result is reported by Foster and Boswell (29). They report a recovery after three years of about 50 percent of the toxaphene applied under similar experimental conditions as above.

The conditions of these two experiments do not resemble the actual use of toxaphene in the study area. Toxaphene is not used as a soil insecticide, and to use a chemical half-life based on incorporation of the material could be misleading. It was mentioned above that the persistence of heptachlor was found to be ten times as long if it is incorporated into soil compared to soil surface applications. A similar variation seems to exist for toxaphene due to its high rate of volatilization, as the following references will indicate.

An experiment of the Entomology Research Division, ARS, USDA, (83) involved the aerial treatment of rangeland with toxaphene for grasshopper control. Only three percent of the amount applied was found in the soil after 84 days following treatment; this rate of disappearance implies a chemical half-life of 17 days. A survey by Stevens, Collier, and Woodham (74) of a number of sites on which toxaphene had been used showed that toxaphene residues could be found on most sites. The article does not specify how the chemical was applied, that is whether it was incorporated into soil or surface applied. The residues for a cotton and vegetable area in which toxaphene had been applied for 8 to 11 years varied between 4 percent and 12 percent of the amount applied. Here the applications had been at relatively heavy rates, averaging between 2 and 7 lbs./A per year. The applications at lower rates (between 1.5 and 3.4 lbs./A per year) to root crops resulted in very low residues, specifically varying from 0 to 4 percent of the amount applied. Higher rates of recovery (varying from 13 percent to 30 percent of the application amount) are given for applications of from 1.8 to 17.3 lbs./acre/year to vegetable crops.

The data of this last report cannot be used to compute a chemical half-life as such. However, it is possible to compare the residue amounts with the computed maximum residue from a first-order degradation function. Such a function estimates the accumulated residue from infinitely many annual applications of a pesticide with a given half-life. Comparison of these theoretically derived residue levels and the residue amounts reported in the publication (74) indicates that the data are consistent with a half-life of toxaphene of less than one year, and in most cases a half-life of one to three months would be indicated.

There is further support for a relatively short half-life of toxaphene from a Wisconsin study of the fate of toxaphene where it was used as a piscicide (Lee, et al. quoted in (79)). Toxaphene residues accumulated in the lake sediment to concentrations as high as 90 parts per million. Here the residues were observed to decrease by a factor of two about every three months.

The disappearance of toxaphene sprayed on cotton plots was studied by Sheets and Bradley (quoted in (79)). Their data indicate that toxaphene is highly resistant to leaching, as less than 0.6 percent of toxaphene applied was lost to washoff during the entire season. The residue in soil six months after the final insecticide application represented only four percent of the total toxaphene applied. Such a rapid loss would be consistent with a half-life of about 0.1 year.

Based on these reports, it seems reasonable to assume a short half-life for toxaphene if it is used in the manner assumed in this study. Since the half-life of toxaphene as reported in these sources varies in the range of less than one month to several months, the half-life of toxaphene assumed for this study is six weeks.

Organophosphate Insecticides

Diazinon

Diazinon appears to be a moderately short-lived insecticide. The degradation mechanism appears to be primarily a chemical hydrolysis rather than a microbial metabolism (51). The degradation rates are closely related to the amount of initial soil adsorption, and the degradation appears to take place at the adsorption sites. Consequently, those factors which increase adsorption are found to decrease the observed half-life of diazinon. Adsorption should vary directly with the amount of organic matter and clay content and be related inversely to the soil pH. Studies of the half-life of diazinon have confirmed these findings.

The percentage of diazinon remaining 4 weeks after application to a silt loam was 47 percent if the soil was held at a pH of 5.5 to 7.0, while a more acid pH (4.3) increased degradation such that only 20 percent remained after the same interval. In comparison, the amount remaining increased to 57 percent for the identical soil held at pH 8.0 (32). In a different experiment, the half-life was reported for two different soil types, ceteris paribus, as 38.8 days for a sandy loam (2.6 percent clay and 2.0 percent organic matter) and 21.6 days for a loam (8.6 percent clay and 2.7 percent organic matter) (15). Other reports give the half-life of diazinon as varying from 2 to 4 weeks (34), as 25 days (35) or with a rather wide variation of 6 to 184 days (63).

A significantly different half-life of diazinon was found in a sandy loam compared to a peaty loam. The authors attribute the variation to differences in organic matter content (1.9 percent for the sandy loam and 17.1 percent for the peaty loam) and cation-exchange capacity (18.1 mequiv N/100g for the sandy loam and 97.2 mequiv N/100g for the peaty loam). The chemical was incorporated into the top 10 cm in each soil. The results showed a half-life of 2 weeks in the sandy loam and 5 weeks in the peaty loam (77).

The chemical half-life of diazinon assumed for this model was 3 weeks in all soil groups except the two bottomland soils. These are highest in organic matter content, and a half-life of 4 weeks was chosen to account for the influence of the organic matter.

EPN

There is a lack of degradation studies involving EPN. Only one experiment (in 1949) included EPN in its treatments. The chemical was applied at 10 lbs./A incorporated 6 inches deep. One year later, no measurable residue was detected using chemical assay and a residue level of 0.2 ppm was detected using chemical assay and a residue level of 0.2 ppm was detected by bioassay (78). The latter residue level is consistent with a half-life for EPN of about 10 weeks. Thus, a half-life of 10 weeks was assumed for EPN.

Ethoprop

Persistence data on ethoprop were found in only one source (37). After an initial lag, the disappearance of ethoprop proceeded quite rapidly, with a half-life of about five weeks. However, the continued degradation was so rapid that less than five percent of the initial amount remained after eight weeks; this amount would imply a half-life of about two weeks if a first-order degradation function had been followed. The article further states that the persistence of ethoprop is effected by wetness and pH of the soil; in each case a shorter persistence is caused by an increase in the factor.

Unpublished data from the manufacturer (42) estimated that persistence is reduced by 50 percent if soil water is at field capacity or if the soil pH is at 8.0 or higher; however, persistence was estimated to increase on reduced tillage fileds.

Based on these data, the half-life of ethoprop was estimated at four weeks on upland soils with conventional tillage, five weeks on upland soils with reduced tillage, 2.5 weeks on the bottomland soils with conventional tillage, and 3.5 weeks on the bottomland soils with reduced tillage.

Fensulfothion

This insecticide is moderately persistent. The major metabolite is fensulfothion sulfone, which is also insecticidally active and which has a longer half-life. The activity of either compound is influenced by the amount of organic or mineral matter in the soil. The sulfone is inactivated by adsorption to mineral matter, while fensulfothion is inactivated by organic matter (38).

A post-emergence spray application of fensulfothion was observed over a period of 28 days. Residues of the O-analogue and the O-analogue sulfone were found, besides amounts of fensulfothion sulfone and the parent compound. The observed residue levels suggest a half-life of fensulfothion, including the metabolites, of between 10 and 25 days. The results for different levels of chemical application and for various time spans within the observed period varied considerably, yet without a discernable pattern, suggesting that other factors may have influenced the results (56).

A study by Chisholm (20) reports a half-life of 3 weeks. Here the chemical was incorporated to a depth of 15 cm (7.5 in.). The estimate of a three week half-life is used in the model.

Fonofos

Fonofos is a moderately persistent insecticide with reported half-lifes ranging from 2 weeks to a high of 22 weeks, with most reports in the 4 to 7 week range. It appears that soil temperature, organic matter content and cation-exchange capacity are the major environmental factors influencing degradation of fonofos.

The longest half-life was reported by Suett (77). He found a half-life of 22 weeks in a peaty loam high in organic matter and cation-exchange capacity, which was twice the half-life observed in a sandy loam low in both variables.

A shorter half-life (28 days) was reported by Schulz and Lichtenstein (71). In this experiment, fonofos was applied as an emulsion at a rate of 10 lb./A incorporated to a depth of 5-6 inches. The data presented suggest a complete cessation of pesticide degradation during the cold fall and winter months. The authors felt that a shorter half-life would have been found if the application rate had been lower.

Results from Western Oregon indicate a half-life of 40 days, applying an emulsion at 4.78 lbs./A double disced and rolled immediately after application (48). The authors describe a degradation curve which is essentially bimodal, and they suggest that the disappearance in the early weeks may be due primarily to physical factors, such as volatilization, while the later stage may reflect the chemical and biological factors such as hydrolysis and metabolism. This suggestion raises the possibility that the very rapid chemical loss reported by Schulz and Lichtenstein may be due to a higher loss to volatilization rather than chemical degradation. A similar result was reported for granular fonofos under summer conditions in Eastern Washington, with a chemical half-life of 47 days (67).

Fonofos was applied at 1 lb./A to a corn field at the Western Iowa Experimental Farm during two growing seasons. The results for both years showed that roughly 25 percent of the amount applied remained after one month and less than 1 percent remained after 4 months (25). These residue levels imply a half-life of slightly over 2 weeks. The half-life assumed for use in this model was 4 weeks.

Phorate

This chemical degrades relatively quickly, primarily to its sulfone. Wide variations in the speed of degradation were reported based on the method of application, with phorate incorporated into soil degrading much slower than surface-applied phorate. This variation appears to be caused by strong adsorption to soil and organic matter.

Phorate appleid to the soil surface was reported to have a half-life of 6 days. The same experiment reports that phorate which was incorporated into soil to a depth of 4 to 5 inches had a half-life of 30 days (61). A similar insecticide treatment (phorate banded and covered with 1 inch of soil) exhibited a half-life of 26 days (72).

Two other studies support the above half-life estimates. One study uses a bioassay method to test residues and found that phorate had degraded completely within one month (68). A similar study gave a half-life estimate of 3.5 days for phorate together with its metabolites (55).

The evidence that phorate adsorbs to clay or organic matter is provided by two studies (16, 37). Specifically, the amount of available (i.e., not adsorbed) phorate of equal amounts applied was greatest in a quartz sand followed (in order) by a sandy soil, clay loam, peat soil, and muck (33).

Phorate was used in the model both incorporated into soil and as a surface treatment. Thus, two different half-life estimates were used for phorate. Phorate incorporated into soil was assumed to have a half-life of four weeks, and surface-applied phorate was assumed to degrade with a half-life of one week.

Terbufos

Terbufos is a new soil insecticide which has only recently been released for use. Consequently, there are relatively few published data on its environmental side-effects. One study has determined that terbufos oxidizes rapidly to the sulfoxide, which in turn oxidizes to terbufos sulfone. The first oxidation is quite rapid, as terbufos has a half-life of four to five days. The sulfoxide reached a maximum concentration at approximately two weeks following incubation. It appeared that the sulfone concentration had not yet peaked at three weeks after treatment. The degradation occurred more rapidly on a soil higher in organic matter with pH 7.0 (54). The sulfone and sulfoxide are equal in insecticidal activity to terbufos, so that a longer half-life should be assumed for environmental purposes than is indicated by the half-life for terbufos alone. A half-life of six weeks was thus suggested for terbufos including its metabolites (53).

Trichlorfon

Trichlorfon is a relatively short-lived chemical with an insecticidal activity half-life of several days. A soil persistence study in northeast Kansas reported a half-life under a variety of environmental conditions. Factors such as reduced tillage or soil type differences cause only insignificant changes in chemical half-life (73). Based on these data, a half-life of five days was assumed for trichlorfon.

Carbamate Insecticides

Carbaryl

Carbaryl degrades fairly rapidly in soil but the reported persistences vary greatly. An experiment using three different application rates of carbaryl tilled into the top six inches of soil demonstrated a half-life of approximately eight days regardless of the initial concentration (45). This experiment found even shorter half-lives of carbaryl in other soils planted to vegetable and fruit crops, with a half-life of three days in spinach and two days in berries; this would suggest that a soil high in organic matter would show a shorter half-life of the chemical. Carbaryl which was surface applied to an apple orchard soil covered with vegetation and decaying plant debris was reported to have degraded within two days to less than 25 percent of the amount found immediately after application (52) which implies a half-life of less than one day. A considerably longer half-life was reported for carbaryl banded into corn furrows and incorporated five cm (2 in.) deep (18). This study found a considerable lag, varying among sample points from 25 to 116 days, before degradation started. However, once degradation began, it proceeded quite rapidly, leading to a 95 percent disappearance within 135 days. The reason for this initial lack of degradation was suggested to be the relatively high chemical concentration until the soil microorganisms had adapted to the chemical. This conclusion is supported by work with carbofuran in which a banded placement produced a brief lag period, and broadcast application exhibited a much faster degradation (19). The only use of carbaryl in the model is as a basal treatment postemergence. In this situation, a half-life of four days was assumed.

Carbofuran

The persistence of carbofuran appears to be strongly influenced by environmental factors. The method of application (i.e., broadcast or in-furrow) caused a difference of 100 percent in the observed half-life (19). A half-life of 46 days was reported for broadcast soil-incorporated applications, disked to 7.5 cm (3 in.) depth. An in-furrow application, disked to a 5 cm (2 in.) depth, was made in a different watershed, which showed a half-life of 117 days. The two fields had pH values of 6.35 and 5.20, and the respective half-lives were assumed to be influenced by the difference in soil pH. A replication in the following year yielded a half-life of 94 days for an in-furrow application on the previously broadcast-treated field. However, the effects were confounded by a temperature difference, which should theoretically account for only 50 percent of the difference, or about 23 days (19).

A study of the persistence of carbofuran on soils in western Washington found the same relationship between soil pH and half-life (31). The chemical degraded 7-10 times faster in a soil of pH 7.9 than in acid and neutral soils (pH 4.3-6.8). The half-life in the alkaline soil was reported as four weeks, while the most acid soil was found to produce a half-life of over 54 weeks. Based on these studies, the half-life of carbofuran was assumed to be six weeks.